

Seattle Distribution System
Corrosion Control Study. Volume I
Cedar River Water Pilot Plant Study

Seattle Dept. of Water, WA

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

1982



U.S. Department of Commerce
National Technical Information Service

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SEATTLE DISTRIBUTION SYSTEM CORROSION CONTROL STUDY

Volume I. Cedar River Water Pilot Plant Study

By

Brian P. Hoyt
Carlos E. Herrera
Gregory J. Kirmeyer
Seattle Water Department
Seattle, Washington 98144

Contract No. R 806686 010

Project Officer

Marvin C. Gardels
Drinking Water Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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ABSTRACT

A study was conducted in Seattle, Washington, to evaluate the use of lime and sodium bicarbonate in surface water supplies to control corrosion of plumbing materials. Continuous-flow pipe-coupon test loops were used to test the effectiveness of two water treatments - addition of lime only, and lime plus sodium bicarbonate. Three commonly used plumbing materials (copper, galvanized steel, and black steel) were tested for corrosion type and rate, penetration rate, and metal leaching. Corrosion rates were evaluated through weight loss, penetration rates were tested with pitting depth measurements, and corrosion types were determined by visual observation. Metal leaching tests were conducted using small-diameter pipes which exaggerate the test results and thus enable meaningful comparisons to be made in short-term tests. This method was developed by the Seattle Water Department for this study.

Results indicate that both the use of lime and lime plus sodium bicarbonate will significantly reduce corrosion in home plumbing systems. Copper and galvanized zinc showed corrosion rate reductions of 65% and 69%, respectively, when lime alone was used, and 56% and 58% when lime plus sodium bicarbonate was used. Both treatments significantly reduced leaching of lead and copper from the metal leaching loops. However, the leaching of zinc and cadmium from galvanized pipe into standing water increased with both treatments.

These tests confirm earlier pilot studies indicating that significant corrosion protection for plumbing materials can be effected by raising both the pH and alkalinity of surface water supplies. However, treatment with lime only is recommended for the Cedar River water supply in view of the overall corrosion protection it affords to commonly used plumbing materials, its costs, and availability. A recommended average dosage of 1.7 mg/L of lime (CaO) at the Lake Youngs outlet will increase pH and alkalinity to 8.3 and 19 mg/L (as CaCO₃), respectively. This dose should achieve an average distribution pH and alkalinity of 7.90 and 18 mg/L CaCO₃ for Cedar water after it passes through open distribution reservoirs and is rechlorinated.

This report was submitted in fulfillment of Grant No. R 806686 010 by the Seattle Water Department under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period from June 1979 to December 1979, and work was completed as of August 1980.

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DISCLAIMER

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

This report presents the results obtained and conclusions drawn from pilot plant research on the corrosion treatment of an aggressive water supply. The data supports the conclusion that substantial corrosion reduction can be achieved by treatment.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

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CONTENTS

Foreword.	iii
Abstract.	iv
Figures	vi
Tables.	vii
Abbreviations and Symbols	viii
Conversion Factors.	ix
Acknowledgment.	x
1. Introduction	1
2. Conclusions.	8
3. Recommendations.	11
4. Equipment Design and Operation	12
5. Analysis and Procedures.	16
6. Results and Discussion	20
7. Benefits of Treatment.	40
References.	42
Appendices	
A. Cedar pH stability tests to compare three corrosion treatment variations	44
B. Quality control data	46
C. Iron pitting analysis results.	53
D. Photographs of pilot plant apparatus	54

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FIGURES

<u>Number</u>		<u>Page</u>
1	Major facilities of the Seattle distribution system.	3
2	Pilot plant flow schematic	13
3	Copper pipe with 50/50 lead/tin solder	14
4	Cedar pilot plant average pH conditions.	19
5	Cedar pilot plant test results - copper coupons weight loss. . .	21
6	Cedar pilot plant test results - iron coupons weight loss. . .	23
7	Cedar pilot plant test results - galvanized steel coupons weight loss.	25
8	Cedar pilot plant test results - copper leaching from copper piping	27
9	Cedar pilot plant test results - copper leaching from copper piping and 50/50 lead/tin solder	29
10	Cedar pilot plant test results - lead leaching from copper piping and 50/50 lead/tin solder	30
11	Cedar pilot plant test results - lead leaching from galvanized steel piping.	31
12	Cedar pilot plant test results - zinc leaching from galvanized steel piping	32
13	Cedar pilot plant test results - cadmium leaching from galvanized steel piping.	33
14	pe-pH diagram for zinc	35

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SECTIONS
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TABLES

<u>Number</u>		<u>Page</u>
1	Percentage of Samples Exceeding EPA Maximum Contaminant Levels	4
2	Recommended Water Quality for the Cedar and Tolt Supplies. . .	6
3	Reduction of Corrosion Effected by Treatment with Lime and Lime plus Sodium Bicarbonate (%)	8
4	Recommended Lime Dosage, Target Water Quality and Chemical Costs.	10
5	Cedar Supply Pilot Test Conditions	14
6	Pipe Types, Metals Analyzed and Analysis Techniques.	18
7	Copper Corrosion Rates, % Reductions and Piping Life Predictions.	20
8	Average Conductivity of Test Loops	22
9	Iron Coupon Weight Loss Results.	22
10	Iron Coupon Penetration Rates and % Reduction.	24
11	Galvanized Pipe Coupon Corrosion Rates and % Reduction	24
12	Metal Leaching Reduction Results from Copper Pipe.	26
13	Average Percent Reduction in Metal Leaching Results from Copper Pipe plus 50/50 Lead/Tin Solder	28
14	Average Percent Change in Metal Leaching from Galvanized Steel Pipe	34
15	Thermodynamic Equations for Aqueous Corrosion of Zinc.	36
16	Savings Realized by Eliminating Feeding of 6.0 mg/L NaHCO ₃ . .	40

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ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

A.A.S.	-- atomic absorption spectrophotometry	MCL	-- maximum contaminant level
°C	-- degrees Celsius	mgd	-- million gallons per day
cm	-- centimeters	mg/L	-- milligrams per liter
cm ²	-- centimeters squared	mg/cm ²	-- milligrams per square centimeter
EIS	-- environmental impact statement	mi	-- miles
EPA	-- U.S. Environmental Protection Agency	mpy	-- mils per year
fps	-- feet per second	m ³ /d	-- cubic meters per day
ft ³ /min	-- cubic feet per minute	RPM	-- revolutions per minute
gal	-- gallons	SWD	-- Seattle Water Department
[Halogen + SO ₄]/Alk	-- [halogen + sulfate] / alkalinity ratio	yr	-- year
in.	-- inches	50/50 Pb-Sn	-- 50% lead, 50% tin solder
ISWS	-- Illinois State Water Survey	µg/L	-- micrograms per liter
L	-- liters	µm	-- micrometers
L/s	-- liters per second	µmhos	-- micromhos

SYMBOLS

C	-- carbon	NaHCO ₃	-- sodium bicarbonate
CaCO ₃	-- calcium carbonate	NH ₄ Acetate	-- ammonium acetate
CaO	-- calcium oxide (lime)	NH ₄ Citrate	-- ammonium citrate
Cd	-- cadmium	NH ₄ OH	-- ammonium hydroxide
CO ₂	-- carbon dioxide	O ₂	-- oxygen
Cu	-- copper	pe	-- -log {e ⁻ }
e ⁻	-- electron	pH	-- -log {H ⁺ }
Fe	-- iron	PH ₂	-- Partial pressure of hydrogen
H ⁺	-- hydrogen ion	PO ₂	-- Partial pressure of oxygen
H ₂ CO ₃	-- carbonic acid	S	-- sulfur
HCO ₃ ⁻	-- bicarbonate	SO ₄ ⁼	-- sulfate
H ₂ O	-- water	Zn ⁺⁺	-- zinc ion
HS ⁻	-- hydrogen sulfide ion	ZnCO ₃	-- zinc carbonate
H ₂ S	-- hydrogen sulfide	ZnO ₂ ⁼	-- zincate
HSO ₄ ⁻	-- bisulfate ion	Zn(OH) ₂	-- zinc hydroxide
HNO ₃	-- nitric acid	Zn(OH) ⁺	-- zincil ion
HZnO ₂ ⁻	-- bizincate	ZnS	-- zinc sulfide
Na ₂ CO ₃	-- sodium carbonate	ZnSO ₄	-- zinc sulfate

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CONVERSION FACTORS

Metric Unit	Multiplier	English Unit
cm	0.394	in.
cm ²	0.155	in. ²
m	3.28	ft
L	0.264	gal
L/s	118.5	ft ³ /min
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km	0.577	mi

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ACKNOWLEDGMENT

Special thanks are due to Mr. Roy R. Jones, Physical Scientist, Region X, U.S. Environmental Protection Agency, for helping the City of Seattle during the grant application and draft review phases, to Sandy Donnelly and Thomas Bykonen for the operation of the pilot plant, and to Ronald Hilburn and Karen Nakhjiri of the University of Washington for draft review.

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SECTION 1

INTRODUCTION

SCOPE

This study is the first of a seven-volume series presenting results of research conducted under the Seattle Distribution System Corrosion Control Study. Volume I, the Cedar River Water Pilot Plant Study, presents pilot test results and recommends specific chemical treatment for internal corrosion control in the Cedar distribution system. Volume II presents the results of a pilot plant study for internal corrosion control in the Tolt distribution system. Volume III evaluates the potential of drinking water contamination from the corrosion of tin/antimony solder. Volume IV evaluates the effectiveness of point-of-use corrosion inhibitor systems. Volume V presents the results of a pilot plant study conducted to determine the effects of chemical treatment on old galvanized pipe. Volume VI presents a laboratory electrochemical technique for corrosion rate determinations in drinking water. Volume VII addresses the problems of corrosion rate aggravation resulting from chlorination and the reduction of disinfection efficiency as a result of corrosion control treatment.

BACKGROUND INFORMATION

Seattle Service Area

The Seattle Water Department (SWD) service area includes Seattle proper and also most of the metropolitan area. It extends from Edmonds on the north to just south of Des Moines, and easterly from Puget Sound to Lake Sammamish at the foot of the Cascade range. Nearly 1 million persons are served directly or indirectly by the Seattle Water Department, which represents about 83% of the population of King County. Average total water consumption is 609,000 m³/d, and summer peak day use has reached 1.3 million m³/d. Approximately two-thirds of this water is sold directly to the SWD retail customers, and the remaining portion is delivered at wholesale rates to suburban water districts and municipalities, who in turn sell it to their direct service customers.

Water Sources

The primary sources of Seattle water are the Cedar and Tolt rivers on the western slope of the Cascade Mountains in eastern King County. These two rivers furnish high quality mountain water of unusual clarity. The Cedar River water supply system, which has been in operation since 1901, serves the southern region of Seattle and parts of South King County. The Tolt, which was added to the City system in 1964, generally serves the area north of the Ship Canal and the water purveyors on the east side of Lake Washington.

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These two sources feed the distribution system from opposite ends, a feature that affords excellent hydraulic characteristics. Figure 1 illustrates the major facilities of the system.

Water Treatment

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Currently, the treatment of both water supplies consists of intake screening, chlorination and fluoridation. Prior to distribution, the water is rechlorinated as it leaves the open in-town reservoirs to assure the free chlorine residual necessary to maintain adequate levels of disinfection. Compared to most other major water utilities in this country, the present treatment is minimal. Many utilities are required to extensively treat their water with coagulation and filtration techniques to render it safe to drink. The SWD's emphasis on watershed protection, together with the large storage reservoir system to meet demands during periods of high turbidity, has enabled Seattle to meet National Interim Primary Drinking Water Regulations¹ without major modifications to the existing facilities.

Existing Facilities on the Cedar River System

The Cedar River system originates in a 370 square kilometer watershed located in eastern King County. 80% of the ownership of the watershed is held by the City of Seattle. The remaining 20% is divided between the United States Forest Service and the Weyerhaeuser Company.

From the watershed, the river flows into Morse Lake, which is located on the site of the naturally occurring inundated Cedar Lake. Water is normally released from Morse Lake back into the natural river channel through a power generating station located at Cedar Falls. Water flows approximately 18 kilometers before being diverted at the Landsburg intake into a 2.44 meter (m) diameter tunnel for transmission to the Seattle area.

At Landsburg, the water is treated by intake screening, chlorination and fluoridation. After treatment, the water can be directed into the distribution system or into Lake Youngs, a large storage reservoir located just southeast of Seattle. Water is again rechlorinated at the outlet from Lake Youngs.

Lake Youngs Corrosion Treatment Facility

In July 1980, a bid to construct a new chemical treatment facility at the outlet from Lake Youngs was accepted by the SWD. The treatment facility includes a lime silo, and lime feeding and pumping equipment. Additional space has been provided at the site for the addition of sodium bicarbonate treatment if needed. The facility is expected to be completed by November 1981.

Internal Corrosion Problem

Water quality deterioration in home and building plumbing systems is a major concern of the SWD. Through several projects that have examined the corrosivity of its water supplies, it is now well documented that corrosion, although not a concern in the distribution system, causes several problems in premise plumbing.² In addition to causing the obvious aesthetic problems of rusty water, red and blue staining and metallic tastes; plumbing corrosion is responsible for a sizable economic burden on Seattle homeowners and possibly

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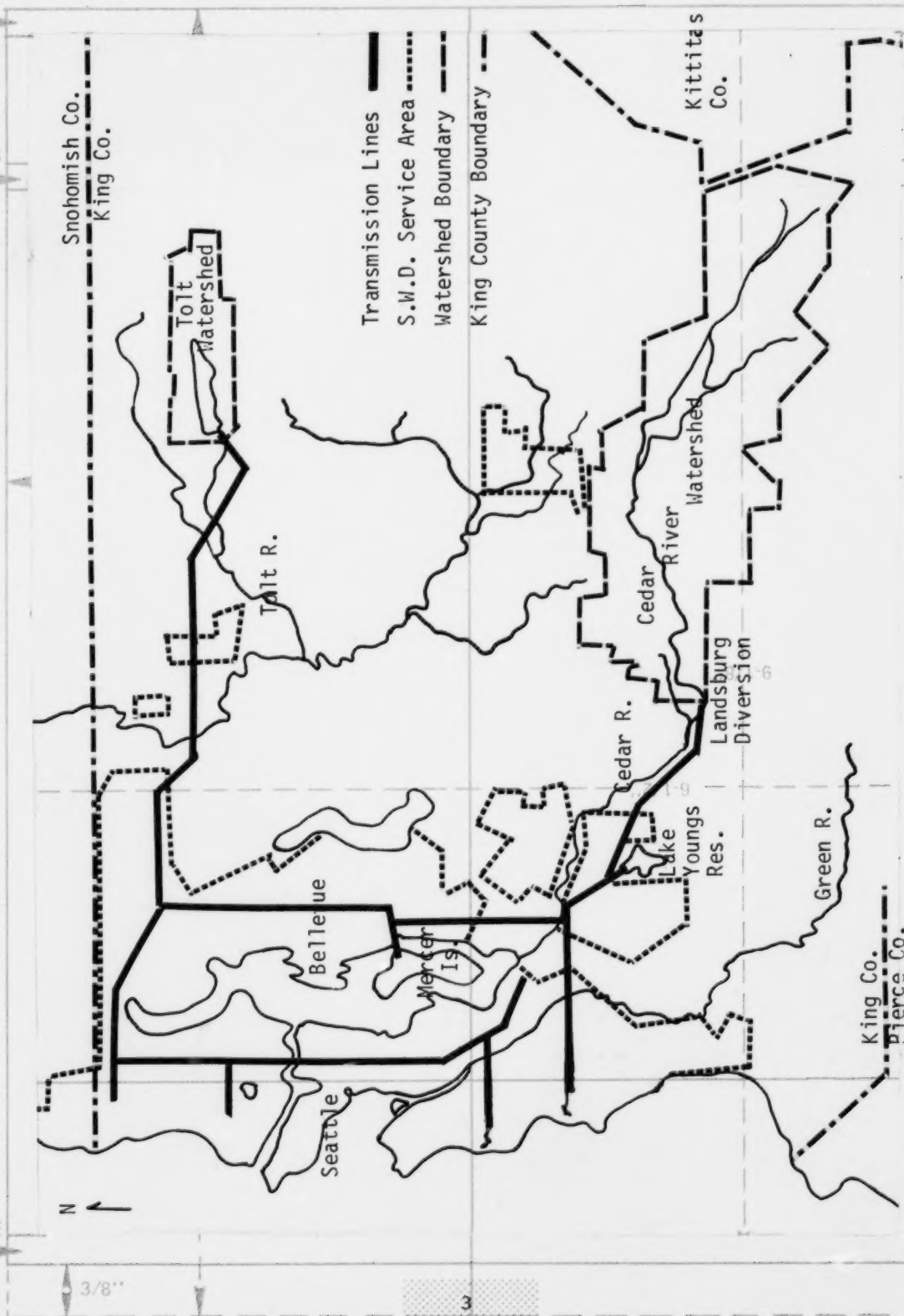


Figure 1. Major facilities of the Seattle distribution system.

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some long term health impacts to those with high environmental exposure to lead.

Aesthetics --

Customer complaints of rusty water, stained fixtures and metallic tastes are frequently received from within the Cedar water distribution system. This problem has been well documented by accurate complaint records and by a questionnaire survey conducted by SWD in 1973. The survey, which was distributed to 10% of all services within the direct service area, showed that 16.7% of customers in the Cedar water distribution system experienced corrosion-related problems.³

Economics --

Significant corrosion of piping occurs in the premise plumbing systems served by the Cedar supply. The average estimated life span of hot water galvanized and copper pipes is approximately 35 years. The forecasted 1978 average annual cost for maintaining serviceability in these pipes was estimated to be approximately \$4 million.⁴

Health Impact --

Further evidence gathered since 1972 demonstrates that the levels of lead (Pb), copper (Cu) and iron (Fe) often exceed Maximum Contaminant Levels (MCL) in overnight standing Cedar tap water (Table 1).

TABLE 1. PERCENTAGE OF SAMPLES EXCEEDING EPA MAXIMUM CONTAMINANT LEVELS

Survey		Primary Contaminants				Secondary Contaminants									
		Lead		Cadmium		Copper		Iron		Zinc		Color		Manganese	
		0.05 mg/L		0.01 mg/L		1 mg/L		0.3 mg/L		5 mg/L		15 units		0.05 mg/L	
Water Supply		R	S	R	S	R	S	R	S	R	S	R	S	R	S
SWMS* (1974-75)	Tolt	0	10	0	0	1	9	19	76	0	1	24	87	0	10
	Cedar	0	16	0	2	0	10	8	60	0	3	0	56	0	0
EPA [†] (1972)	Tolt	0	23	0	9	3	23	15	73	0	9	-	-	0	5
Kennedy [‡] Engr/SWD (1976)	Tolt	0	0	0	0	0	0	0	100	0	0	-	-	0	0
	Cedar	0	0	0	0	0	0	0	40	0	9	-	-	0	0
TOTAL	Tolt	0	13	0	2	2	11	17	76	0	3	24	87	0	7
	Cedar	0	14	0	2	0	10	11	59	0	3	9	56	0	0
	Tolt & Cedar	0	13	0	2	1	11	14	69	0	3	12	73	0	5

R = Running cold water samples.

S = Overnight standing cold water samples.

*Seattle Water Metals Survey.

[†]Study of Corrosion Products in the Seattle Water Department Tolt Distribution System.⁶

[‡]Internal Corrosion Study.⁴

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Cadmium (Cd) and zinc (Zn) were also found to increase after overnight standing in home plumbing; however, they rarely exceeded their MCL's.

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Although the health impact of overnight standing water metal levels is not an acute problem, it would be desirable to reduce exposure to metals, especially lead and cadmium.

Causes of Corrosion

The corrosiveness of Cedar water results from several related factors, which include:

Acidity as indicated by low pH; the raw Cedar water pH is approximately 7.6; after chlorination and fluoridation, pH is reduced to a range of 6.8 to 7.2;

A dissolved oxygen concentration that is at saturated conditions;

Insufficient calcium and bicarbonate alkalinity in the water to form protective calcium carbonate films on pipe surfaces;

A relatively high [halogen + sulfate] / alkalinity ratio $[(\text{Halogen} + \text{SO}_4) / \text{Alk}]$ of 0.5 to 0.8 which results in conditions favorable to pitting corrosion.

In 1970, three factors combined to intensify the corrosiveness of both water supplies: (1) To decrease the occurrence of positive bacteriological samples within the distribution system, the chlorine dosage at the open reservoir outlets was increased. (2) At the request of the U.S. Public Health Service, ammoniation of the water supply was stopped to enable a free chlorine residual to be maintained throughout the distribution system. This change from combined chlorination to free chlorination was implemented to provide quicker, more effective disinfection of the unfiltered water supply. (3) Based on a vote of the Seattle citizens in 1968, fluoridation with hydrofluosilicic acid began in 1970.

Internal Corrosion Study⁴

In December 1975, the City of Seattle retained a consulting engineering firm to perform a detailed analysis of the corrosion problem and to recommend possible solutions. The Internal Corrosion Study, which included a nine-month pilot plant investigation, confirmed the corrosiveness of Seattle water, the causes of corrosion, and the impacts associated with the corrosive water. The study also evaluated alternative measures to reduce the corrosiveness of the water supply. Corrosion reduction alternatives investigated included alternative methods of disinfection and fluoridation, blending with ground-water supplies, and the addition of corrosion inhibitor chemicals.

Based on the findings of the consultant study and the conclusions of pilot plant investigations, an Internal Corrosion Control Management Plan was developed. Because the very low level of mineral solids, pH, and alkalinity constitute the major causes of the waters' corrosiveness, the proposed plan was designed to correct the natural deficiency of minerals in Seattle's

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mountain water. The natural deficiency of calcium and carbonate/bicarbonate alkalinity ions was proposed to be corrected by the addition of lime and sodium bicarbonate to achieve the water quality shown in Table 2.

The combination of lime and bicarbonate was chosen because higher levels of alkalinity can be reached at pH 8.3 with this combination than with combinations of other commonly used corrosion inhibitors, specifically lime and sodium carbonate. Although the consultant recommended lime and sodium bicarbonate treatment, the actual chemical combination was not extensively tested in their pilot studies.

STUDY OBJECTIVES

The formal objective of this research effort was to determine whether lime plus sodium bicarbonate treatment or lime treatment alone is better in controlling internal plumbing corrosion in Cedar water. The scope of work included:

1. Determining the corrosion rates, penetration rates and corrosion types from galvanized steel, copper and black steel piping materials exposed to control, lime treated, and lime/sodium bicarbonate treated water.
2. Determining tap water metal leaching associated with each treatment from copper pipe, 50/50 Pb-Sn solder and galvanized steel pipe.
3. Predicting increases or decreases in residential pipe life spans associated with each treatment.
4. Establishing the required optimal full-scale chemical dosages for both treatments.

TABLE 2. RECOMMENDED WATER QUALITY FOR THE CEDAR AND TOLT SUPPLIES

Parameter	Existing Water Quality	Proposed Water Quality with Corrosion Treatment
pH	7.2	7.8-8.3*
Total Alkalinity, mg/L CaCO ₃	14-18	20-25
Halogen + SO ₄ ⁼ /Alk Ratio	0.5-0.8	<0.5

*A pH of 8.3 was determined as the practical upper limit for pH adjustment. This pH limit was chosen because pH >8.3 in the Tolt supply may cause excessive trihalomethane formation⁴ and at pH above 8.3, the disinfection power of free chlorination is considerably reduced.⁷ In addition, it may be desirable to maintain approximately equal water chemistry in both supplies to minimize aesthetic corrosion problems in Tolt/Cedar mixed distribution zones.

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During the period from June 1979 to December 1979, three continuous flow corrosion test apparatus (control, lime and lime/bicarbonate treatment) were operated at Seattle's Beacon Hill Reservoir. This test site was chosen within the Cedar distribution system in order to conduct the corrosion testing with the same water quality as is delivered to the SWD customer.

The corrosion coupon tests used documented average corrosion rates based on weight loss, penetration rates based on pit depths, and corrosion types based on visual observations. Coupons were made of 2.54 centimeter (cm) diameter pipe segments of iron, galvanized steel and copper.

Metal leaching tests for Cu, Pb, Cd, and Zn were performed on separate 0.635 cm diameter pipe sections attached to the main test apparatus. This is a new method which has been developed by SWD for this study.

STUDY ELEMENTS

The study consisted of the following three primary elements that included various secondary topics.

Corrosion Control Treatment

1. Treatment effectiveness.
2. Comparison of treatments.
3. Comparison of treatment costs.

Methods of Analysis

1. Metal coupon analysis techniques.
2. Development of metal leaching evaluation method.

Corrosion Characterization

1. Corrosion types.
2. Determination of corrosion rates and penetration rates.
3. Plumbing life spans.
4. Metal leaching.

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SECTION 2

CONCLUSIONS

COMPARISON OF CHEMICAL TREATMENT ALTERNATIVES

A comparison of the effectiveness of the chemical treatments used in the Cedar River Pilot Plant Study is presented in Table 3.

TABLE 3. REDUCTION OF CORROSION EFFECTED BY TREATMENT WITH LIME AND LIME PLUS SODIUM BICARBONATE (%)

Treatment	COPPER/ COPPER LEAD/TIN SOLDER CORROSION CORROSION				GALVANIZED STEEL CORROSION				BLACK STEEL CORROSION	
	Corrosion Rate by Weight Loss	Copper Leaching (0.15 m/s)	Copper Leaching (0.15 m/s)	Lead Leaching (0.15 m/s)	Corrosion Rate by Weight Loss	Lead Leaching (0.15 m/s)	Zinc Leaching (0.15 m/s)	Cadmium Leaching (0.15 m/s)	Corrosion Rate by Weight Loss	Pitting
CONTROL	0	0	0	0	0	0	0	0	0	0
LIME	65	46	78	81	69	49	-138	-32	6	6
LIME/ BICARBONATE	56	47	76	84	58	72	-152	-51	*	12

*Not calculated due to weight loss determination error.
m/s = meters per second.

Each evaluation criterion is explained below:

1. Corrosion rate by weight loss - The percent reduction of corrosion rates based on weight loss.
2. Pitting - The percent reduction of penetration rates based on pitting data.
3. Metal leaching - The average reduction of metal concentrations during the 0.15 m/s flow testing period.

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Table 3 indicates the following conclusions for each chemical treatment alternative:

Lime Treatment

The lime treatment produced the best overall protection against corrosion and metal leaching. It proved superior to lime/bicarbonate treatment in the reduction of copper, galvanized steel and black steel corrosion rates based on weight loss analysis; and in the reduction of copper penetration rates based on pitting depths. Comparable copper leaching and lead leaching reductions from the copper plus lead-tin solder test sections and comparable copper leaching reductions from the copper test sections were obtained using either treatment method.

Lime/Bicarbonate Treatment

The lime/bicarbonate treatment produced distinctly better reduction than the lime treatment in only two evaluation criteria: lead leaching from galvanized steel pipe and black steel penetration rates based on pitting determinations. — 6-1/2" —

No Treatment

The control tests demonstrated greater corrosion rates and metal leachate levels with two exceptions, zinc and cadmium leaching from new galvanized steel pipe was actually increased under both treatment conditions. This apparent discrepancy is discussed in Section 6.

PROPOSED CHEMICAL TREATMENT

The results of the pilot plant test program presented previously demonstrate that lime treatment is the most appropriate chemical treatment for the Cedar water supply. Table 4 details the recommended lime dosage, target water quality and chemical costs.

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TABLE 4. RECOMMENDED LIME DOSAGE, TARGET WATER QUALITY AND CHEMICAL COSTS

Item	Present Conditions	With Lime Treatment
Treatment Plant CO ₂	2.7*	0.0 mg/L
Treatment Plant pH	7.2*	8.3
Average Total Alkalinity, CaCO ₃	16*	19 mg/L
Atmospheric Equilibrium pH @ 15°C	7.79	7.86
Minimum Distribution pH	7.0*	7.65 [†]
Estimated Average Distribution pH	7.15*	7.90
Average Distribution Conductivity	54.5*	58.2
(Halogen + SO ₄ ⁼)/Alk Ratio	.5-.8	.4-.7
Average Lime Dosage (CaO)	-	1.7 mg/L
Lime Cost per Year (\$)	-	13,000 [‡]

*Based on SWD water quality monitoring data.

[†]By calculation.

[‡]Based on cost of lime delivered to Lake Youngs - June 1981.

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SECTION 3

RECOMMENDATIONS

GENERAL

This section of the report makes recommendations regarding additional research needs and further evaluations in the area of corrosion control.

SEATTLE WATER DEPARTMENT

The SWD should:

- Implement lime treatment of the Cedar River source to increase pH and alkalinity to reduce corrosion of premise piping.
- Determine to what extent chemical treatment for corrosion control decreases the disinfection power of free chlorine.
- Monitor bacteriological water quality in the Cedar distribution system before and after the implementation of full-scale treatment.
- Evaluate the possibility of trihalomethane formation in Cedar water with respect to chemical treatment.
- Determine whether corrosion treatment will cause post-precipitation problems in the Cedar system.

U.S. ENVIRONMENTAL PROTECTION AGENCY

The EPA should:

- Develop a standard corrosion test loop for corrosion analysis of drinking water.
- Develop a method for the determination of metal leaching from plumbing materials.
- Publish a state-of-the-art manual for corrosion control of drinking water.

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SECTION 4

EQUIPMENT DESIGN AND OPERATION

PILOT TEST APPARATUS

Continuous Flow Test Unit

The continuous flow test unit illustrated in Figure 2 followed the descriptions for ASTM D2688-C-75, otherwise known as the Illinois State Water Survey (ISWS) test apparatus.⁸ This same basic equipment was used earlier by the consultants⁴ for evaluations of lime/soda ash, lime/Zn-PO₄, and NaO/SiO₂ on Cedar and Tolt water supplies. Each complete loop contains four 10.2 cm long pipe segment coupons (2.54 cm diameter) of copper, galvanized iron, and steel pipe that meet ASTM Standard D2688-C-75. The coupons are placed within the loop in order of increasing nobility.

A velocity of 0.30 m/s was maintained through the 2.54 cm diameter pipe coupons. Flows through the loops were held stable through the use of a constant head reservoir with approximately 3.66 m head. The reservoir was constructed of a 1.2 m section of 15.2 cm diameter cast iron pipe with a welded plate over one end. Three 1.91 cm outlets were tapped into the base and 1.59 cm black rubber hose was run to the test loops. The overflow was attached 0.30 m from the top to provide a constant surface level.

Chemicals were fed by three AMF CUNO diaphragm pumps. The chemicals used were hydrated lime [Ca(OH)₂] and sodium bicarbonate (NaHCO₃). Feed solutions of the full strength chemicals [150 g Ca(OH)₂/151 L; 600 g NaCO₃/151 L] were mixed in 151 L plastic buckets. The feed solutions were then pumped from the solution buckets into the test units just before the static mixer.

Metal Leaching Test Loops

In addition, short sections 25-51 cm of 0.635 cm pipe were attached to the continuous flow test units for comparison of Cu, Pb, Zn, Cd, and Fe leaching under the two alternative treatments. The leaching pipe sections were made of copper, copper plus 50/50 lead/tin (Pb-Sn) solder, galvanized steel (new), and black iron pipe. Two velocities were used (0.061 m/s and 0.15 m/s) in establishing corrosion films in the metal leaching sections. Dissolved metals were determined after periodic 22 to 24 hour contact with test water in the laboratory.

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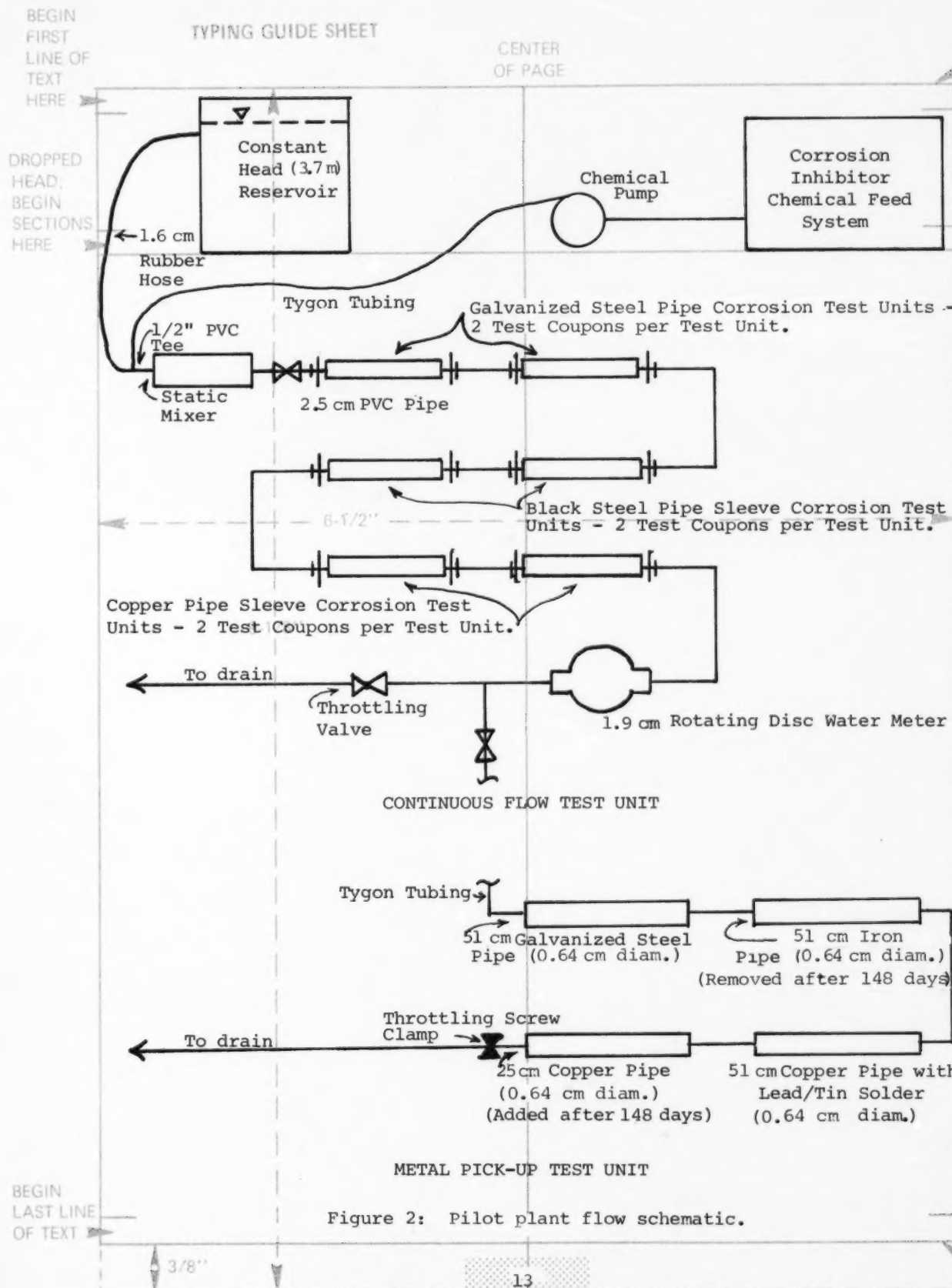
The construction of the 0.64 cm copper pipe with the 50/50 Pb-Sn solder can be seen in Figure 3. This design allows for uniform surface areas of

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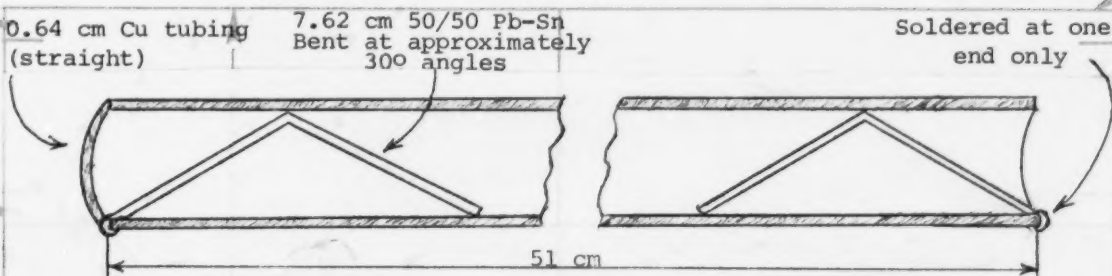


Figure 3. Copper pipe with 50/50 lead/tin solder.

Cu and solder with intimate contact between the pipe and the solder. It exaggerates the lead leaching levels found in soldered copper pipe and therefore promotes meaningful comparison of the treatments.

Small diameter pipes were chosen for the metal leaching tests because they have a high surface area-to-volume ratio which also exaggerates results; are easy to manipulate and control flow; and produce an adequate quantity of leachate for testing.

CHEMICAL TREATMENT

The test treatment conditions were chosen to simulate average distribution system levels of pH and alkalinity. Carbon dioxide (CO₂) uptake in open distribution reservoirs and conversion of bicarbonate to CO₂ by post-reservoir chlorination will lower pH and alkalinity from treatment plant levels. Laboratory tests (presented in Appendix A) were performed to estimate these changes. Table 5 presents the expected average distribution water quality with lime and lime/bicarbonate treatments.

TABLE 5. CEDAR SUPPLY PILOT TEST CONDITIONS

Item	Loop #1 Control, Cedar Pipeline	Loop #2 Lime	Loop #3 Lime + Bicarbonate
pH	7.1-7.4	7.90	7.95
Alkalinity (mg/L CaCO ₃)	>14.5	+2 (>16.5)	+5.6 (>20.1)
Chlorine Residual (mg/L)	~.2-.4	~.2-.4	~.2-.4
Lime Dosage, CaO (mg/L)	0	1.1	~1.1
NaHCO ₃ Dosage (mg/L)	0	0	~6.0
[Halogen + SO ₄ =] / Alk	.5-.8	.4-.7	.3-.6

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Loop #3 lime and bicarbonate dosages were chosen to produce a bicarbonate/lime molar ratio of 3.6 and to produce the total alkalinity and [Halogen + $\text{SO}_4^{=}$]/ Alk ratio as specified by the consultant during earlier studies.⁴ A sodium bicarbonate/lime molar ratio of 2.0 is equivalent to treatment with soda ash (Na_2CO_3), a less expensive chemical treatment than lime plus bicarbonate. A potential advantage in using lime plus bicarbonate over soda ash is that a higher alkalinity can be obtained without exceeding the target pH, providing the molar ratio is greater than 2.0.

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SECTION 5

ANALYSIS AND PROCEDURES

METAL PIPE COUPON ANALYSIS

Corrosion Rates

Average corrosion rates were calculated by a two-step process: (1) Weight loss in milligrams per square centimeter (mg/cm^2) versus time was plotted for each metal and treatment; (2) the least squares slope ($\text{mg}/\text{cm}^2/\text{day}$) of the last three usable points of the weight loss curve was calculated and converted to mils per year (mpy). The calculated slope is a tool for comparison and except for copper, is only an approximation of long-term corrosion rates. For copper, the relationship between weight loss and time is linear, therefore corrosion rate is constant. For galvanized steel and iron, corrosion rates decrease with time and therefore can only be approximated.

Penetration Rates

Penetration rates were determined for the copper and black steel coupons. The coupons were split into quarters and the pit depths were measured using either a pointed tip micrometer (iron specimens) or a binocular microscope with a graduated fine focus adjustment (iron and copper specimens). Penetration rates were then calculated in mpy based on the average of the ten deepest pits on each specimen.

Penetration rates were not determined for the galvanized steel coupons because an uneven galvanized layer on the coupon and a general thinning type corrosion caused large inaccuracies in pit depth measurements.

Metal Coupon Preparation

Coupons were prepared as directed in ASTM D2688-C-75⁸ except as follows: They were scrubbed with non-chlorinated Bon Ami cleanser, rinsed with water, rinsed with denatured alcohol, and finally rinsed with alcohol/acetone/xylene. Prepared coupons were stored in a desiccator.

Prior to insertion in the loops, the coupons' outer surfaces were coated with a very light film of silicone grease. They were then sealed in plastic holders with silicone seal gasket material at each end to prevent water from contacting the outer surface of the coupons. Coupons were identified by punching a letter-number code on the outside.

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Post-Exposure Cleaning Procedure

Post-exposure cleaning procedures were as follows:

1. The coupons were scraped with a plastic spatula and/or scrubbed with Bon Ami and a brush to remove loose deposits;
2. This was followed by chemical cleaning per the recommended procedures given in Corrosion Testing Procedures.⁹
 - I. Copper: Scrubbing with Bon Ami only.
 - II. Iron: 20% NH₄ CITRATE/10% NH₄OH at 70-75°C for 10 minutes; repeat Step #1.
 - III. Galvanized Iron: Saturated NH₄ ACETATE for 10 minutes (room temperature); repeat Step #1.
3. Final washing in alcohol/xylene/acetone solvent, air dry, desiccate.

6-1/2"

METAL LEACHING TESTS

The metal leaching test loop sections were periodically removed during the study. The pipe sections were filled with test water from their respective loops, the ends were sealed with parafilm and then allowed to stand horizontally at room temperature for 22 to 24 hours. After this period, the water was filtered through a 0.45 μ m Millipore membrane filter, preserved (.5% HNO₃ in Pyrex) and analyzed for metals by flame and flameless atomic absorption spectrophotometry according to Methods for Chemical Analysis of Water and Wastes.¹⁰ Background metal concentrations were determined after passing the test waters through the same filtration apparatus, and these values were subtracted from the levels found after leaching.

Table 6 lists the pipe types, metals analyzed and analysis techniques.

QUALITY CONTROL

Daily pH and flow measurements and adjustments, and apparatus maintenance were performed to provide quality control over the test conditions. To document alkalinity and NaHCO₃ feed in Loop #3, alkalinity tests were performed twice weekly. All measurements were performed according to "Standard Methods."¹¹

Figure 4 illustrates the average pH values $\pm$ the standard deviation and demonstrates that excellent consistency was maintained in all three test loops. Complete quality assurance data is summarized in Appendix B.

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TABLE 6. PIPE TYPES, METALS ANALYZED AND ANALYSIS TECHNIQUES

Metal Tested	Analysis Method	Test Pipe Section
Pb, non-filterable	Flameless A.A.S.*	Galvanized; Cu + 50/50 Pb-Sn solder.
Cd, non-filterable	"	Galvanized; Cu; Cu + 50/50 Pb-Sn solder.
Cu, non-filterable	Flame A.A.S.	Cu; Cu + 50/50 Pb-Sn solder.
Zn, non-filterable	"	Galvanized.
Pb, total	"	Galvanized.
Cd, total	"	Galvanized.
Fe, total	"	Iron.
Zn, total	"	Galvanized.

*A.A.S. = Atomic Absorption Spectrophotometry.

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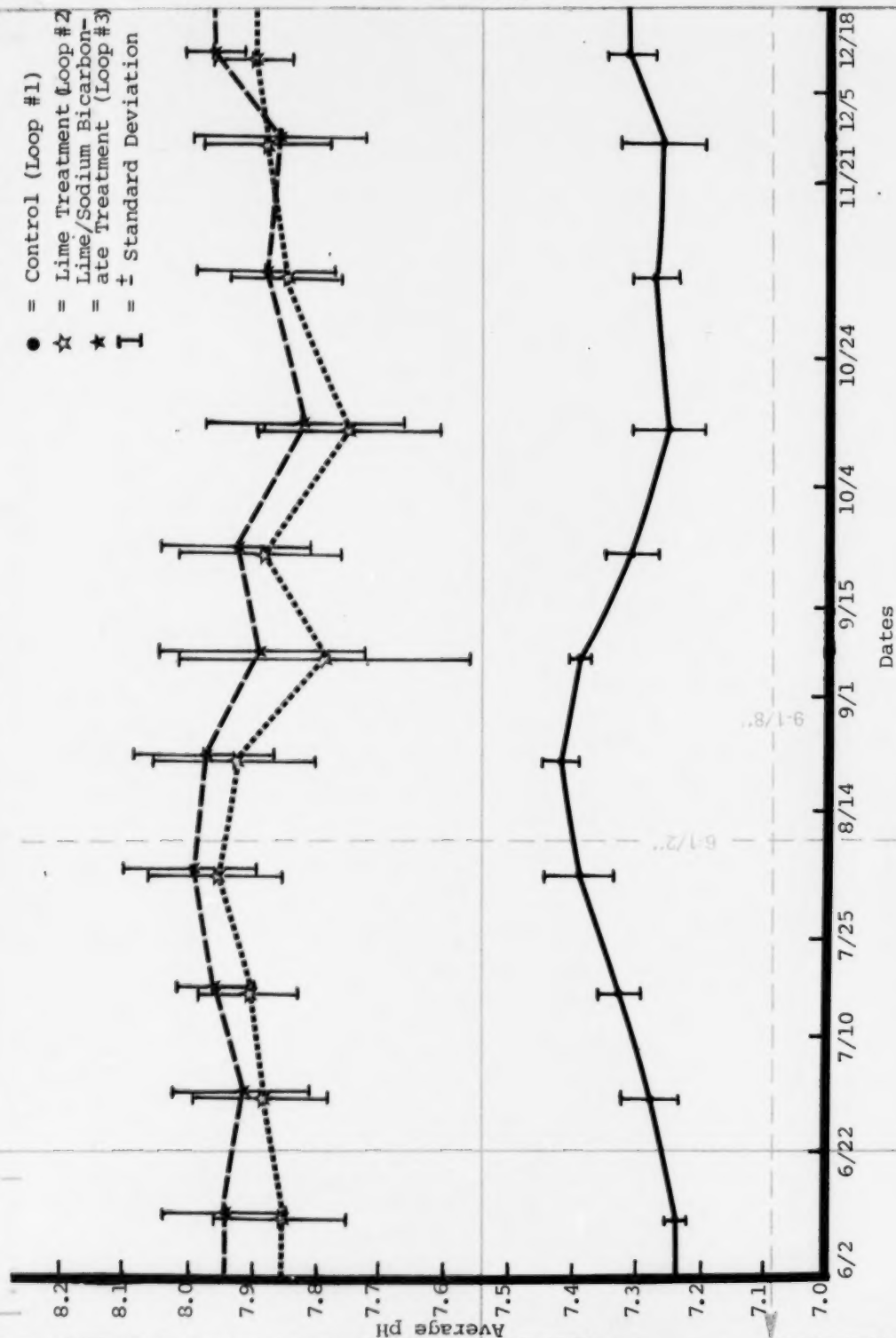


Figure 4. Cedar pilot plant average pH conditions.

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SECTION 6

RESULTS AND DISCUSSION

METAL COUPON TESTS

Copper

Copper corrosion in Cedar water is of a uniform thinning nature, with numerous, very small, shallow pits. Corrosion rates in Cedar water stabilize in several weeks and only very thin corrosion films are formed. For these reasons, average coupon corrosion rates based on weight loss are excellent approximation of the actual premise plumbing corrosion rates.³

Copper weight loss versus time is presented in Figure 5. Corrosion rates generated from this data indicate that both treatments reduce the corrosion rates by more than 50%, thereby extending copper pipe life by better than a factor of 2 (see Table 7).

TABLE 7. COPPER CORROSION RATES, % REDUCTIONS AND PIPING LIFE PREDICTIONS

Treatment	Slope* (mg/cm ² /day)	Corrosion Rate mpy [†]	Corrosion Rate % Reduction	Average Piping Life [‡] (Years)
Control	.0411	.66	0	35
Lime	.0141	.23	65	100
Lime/Sodium Bicarbonate	.0179	.29	56	80

*Slope of least squares fit of all data points.

†Slope x 16.1 (density factor).¹²

‡Based on Kennedy Engineers⁴ original pipe life estimate for Type M copper, hot water service.

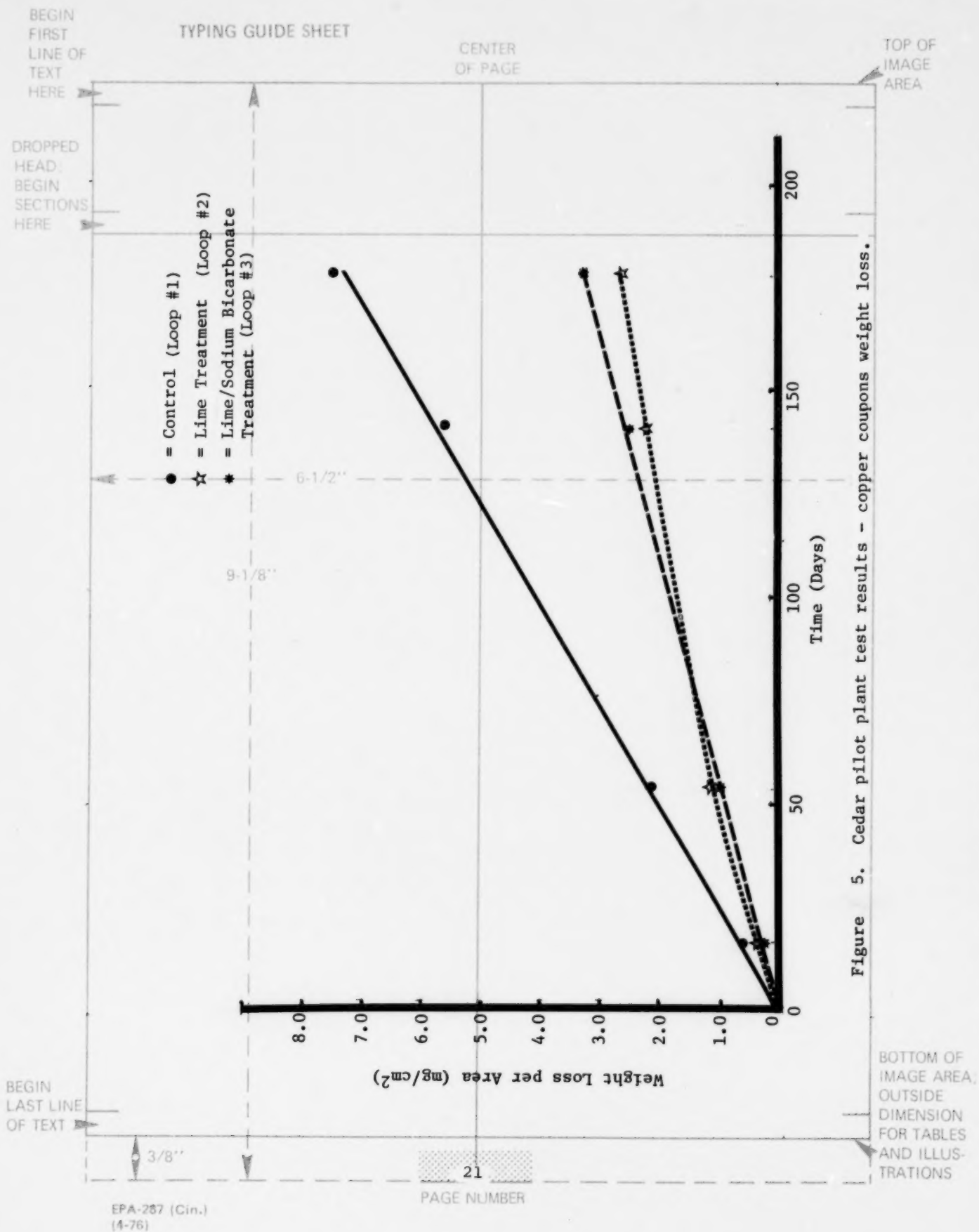
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The slightly superior performance of lime treatment (at a lower pH) was somewhat surprising. Initially it was suspected that the greater corrosion rate in Loop #3 was a result of its higher flow rate [0.158 liters/second (L/s) for Loop #3 versus 0.147 L/s for Loop #2]. However, the mid-study increase in flow from 0.149 to 0.179 L/s in Loop #1 did not increase the corrosion rate. (These differences in flow were due to operational error.) The corrosion rate difference between Loops #2 and #3 therefore appear to be valid and may be caused by the higher conductivity in Loop #3 as shown in Table 8.

Iron

The iron corrosion after 170 days exposure was consistently of a semi-local uneven type, with a small number ($\sim 3/\text{cm}^2$) of wide pits (width/depth ~ 4). The pits which developed were usually oblong with the longest dimension in the direction of flow. The pipe specimens exposed to raw water usually had the greatest percentage of surface area attacked. Pitting depth and penetration rates, however, showed no appreciable decrease as a result of chemical treatment. Generally, a reduction in the rate of pitting with time was observed. 6-1/2"

Weight loss versus time for iron is illustrated in Figure 6. Anomolous results clouded much of the findings for weight loss and penetration rates and thus the results in Tables 9 and 10 cannot be presented with the same certainty as the copper specimens.

TABLE 8. AVERAGE CONDUCTIVITY OF TEST LOOPS

	Loop #1 Control	Loop #2 Lime	Loop #3 Lime + Bicarbonate
Average Conductivity, μmhos	56.1	59.8	66.0
Increases Over Control	-	+3.7	+9.9

TABLE 9. IRON COUPON WEIGHT LOSS RESULTS

Treatment	Slope ($\text{mg}/\text{cm}^2/\text{day}$)	Corrosion Rate (mpy)*	% Reduction
Control	.364	6.66	0
Lime	.343	6.28	6
Lime/Sodium Bicarbonate	†	†	†

* $\text{mpy} = \text{Slope} \times 18.3$ (density factor).¹²

†Not calculated.

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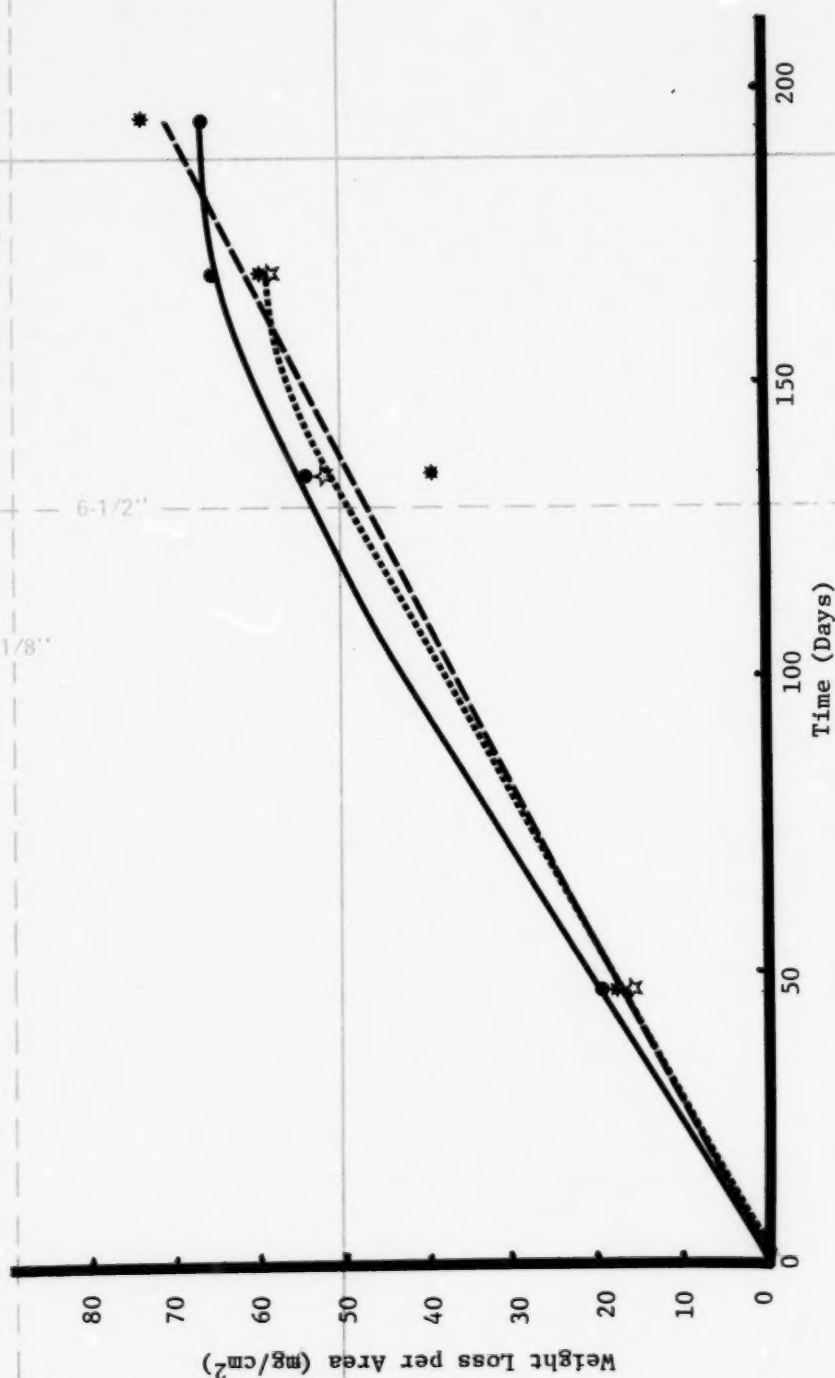


Figure 6. Cedar pilot plant test results - iron coupons weight loss.

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TABLE 10. IRON COUPON PENETRATION RATES AND % REDUCTIONS

Treatment	Average Penetration Rate (170- & 193-day coupons), mpy	% Reduction
Control	26.7	0
Lime	25.2	6
Lime/Sodium Bicarbonate	23.5	12

The weight loss data for Loop #1 and Loop #2 follow typical corrosion curves and indicate a slight rate reduction for lime treatment. Loop #3 data points are very inconsistent and therefore corrosion rates were not calculated. Penetration rates were erratic, except for Loop #3, making comparisons difficult. As shown in Table 10, an average of the last two data points indicates small reductions in penetration rates for both treatments with lime/bicarbonate slightly better than lime alone. (See Appendix D for complete iron pitting descriptions.)

Based on this information, it is expected that little improvement will follow corrosion treatment for iron or old galvanized steel pipes which have iron exposed.

Galvanized Steel

The galvanized steel pipe specimens demonstrated general even corrosion which did not penetrate the galvanized layer. For this reason, no pit depth data was obtainable and the evaluation is based solely on weight loss data. It should be noted that this data is representative of new galvanized pipe corrosion and not representative of older (>2-5 years) pipe, which has both iron and zinc exposed to the water. Once the galvanized layer is penetrated, the corrosion of galvanized pipe is similar to the corrosion of iron pipe.

As shown in Table 11, both treatments produced large reductions in corrosion rates.

TABLE 11. GALVANIZED PIPE COUPON CORROSION RATES AND % REDUCTION

Treatment	Slope (mg/cm ² /day) [†]	Corrosion Rate (mpy) [*]	% Reduction
Control	.115	2.32	0
Lime	.0367	0.74	68
Lime/Sodium Bicarbonate	.0466	0.94	59

^{*}mpy = Slope (mg/cm²/day) x 20.2 (density factor).¹²

[†]Slope = Least squares fit last 3 points; Loops #2 and #3; all points Loop #1.

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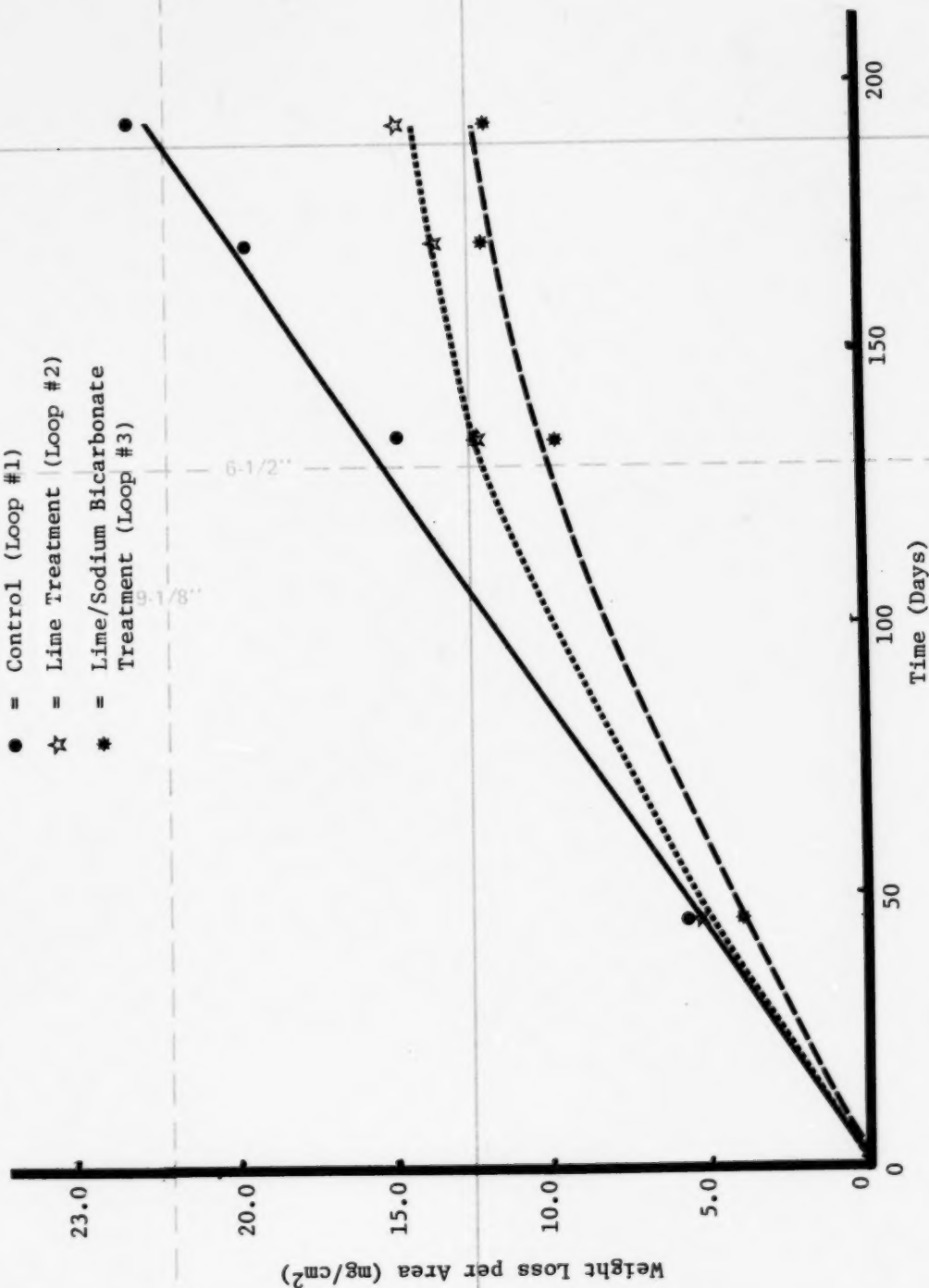


Figure 7. Cedar pilot plant test results - galvanized steel coupons weight loss.

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From Figure 7, corrosion rates were calculated using the slope of the least squares fit line through the last 3 data points for Loops #2 and #3, where distinct tapering off occurred, and all 5 points for Loop #1 where the rate remained constant.

The data in Table 11 is very much in agreement with previous weight loss data generated for lime/soda ash treatment of Cedar water using the same type of test apparatus.⁴

METAL LEACHING

The treated water's impacts on leaching of lead, cadmium, copper, and zinc during 22-24 hour contact time with plumbing materials was determined as described in Section 5. Iron leaching tests (total iron) were attempted and discontinued because the results were very inconsistent and the iron corrosion products tended to coat the downstream test pipes at the low velocity (0.061 m/s).

The velocities through the test sections were set at 0.061 m/s for the first 148 days of testing. Since the leach tests were intended to show exaggerated metal levels for best comparison of treatments, and since the copper and lead levels from the copper plus solder control section stabilized to levels no greater than many Seattle residential tap samples, the velocities were increased to 0.15 m/s for the remainder of the test. The velocity increase was designed to accelerate corrosion and in most instances did so.

Copper Pipe

Copper pipe was analyzed for copper and cadmium leaching. In Figure 8, although there are only three data points for each treatment alternative, certain trends are evident. Both chemical treatments equally reduced copper leaching. Table 12 indicates the percent reductions in dissolved copper obtained.

A very small amount of dissolved Cd ($< 1 \mu\text{g/L}$) was found in all leachate samples indicating some impurity in the copper tubing.

TABLE 12. METAL LEACHING REDUCTION RESULTS FROM COPPER PIPE

Treatment	Average % Reduction of Dissolved Copper
Control	0
Lime	46.4
Lime + NaHCO_3	47.6

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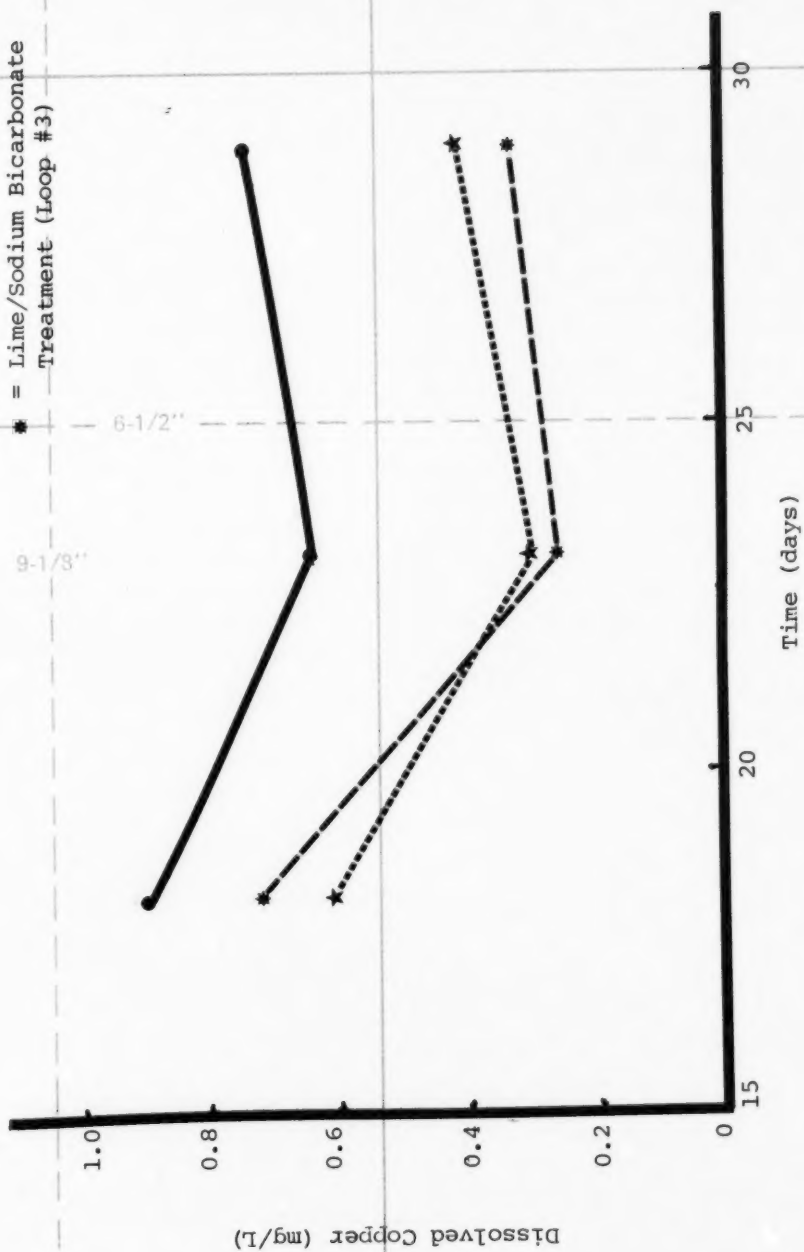


Figure 8. Cedar pilot plant test results - copper leaching from copper piping.

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Copper Pipe and 50/50 Lead/Tin Solder

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Copper and lead leaching from copper pipe with 50/50 lead/tin solder was measured and is presented in Figures 9 and 10. Average percent reductions in dissolved lead and copper are presented in Table 13.

Again, both the lime and lime/bicarbonate treatments performed equally well in reducing copper leaching. At the end of the experiment, percent reduction of copper leaching exceeded 76%. Dissolved copper levels were usually lower in the copper plus solder test loop than in the copper pipe test loop. This is a result of the sacrificial corrosion of the lead/tin solder when placed in contact with the more noble copper.

Dissolved lead levels, generally, were initially quite high and decreased with time. Both treatments substantially reduced lead leaching. The leaching of lead from the specimen exposed to lime/bicarbonate treatment stabilized quicker than that exposed to lime treatment, although after 148 days exposure both treatments reduced lead leaching to the same levels.

The increase in flow at 149 days was followed by a sharp increase in both copper and lead leaching from the control test loop. In contrast, only minimal increases in metal leaching from both treatment loops correspond to the flow increase. This is quite significant because it indicates that the protective corrosion films formed on premise plumbing systems under treatment conditions are more stable, have better adherency and greater resistancy to flow changes than the films formed under untreated conditions.

Galvanized Steel Pipe

Water from the galvanized steel pipe was analyzed for zinc, lead, and cadmium levels. Table 14 shows that both treatments reduced the amount of lead leaching and increased cadmium and zinc leaching.

Figure 11 demonstrates that lime/bicarbonate treatment gave better lead leaching reduction results than lime treatment. Again, the flow increase from 0.061 to 0.15 m/s resulted in greater increases in lead leaching in the control loop than in the treatment loops.

The increases in cadmium and zinc dissolution from galvanized steel pipe as a result of treatment, illustrated in Figures 12 and 13, appears to be in contrast with the results obtained from the weight loss coupon analysis. This discrepancy is explained in the following paragraphs.

TABLE 13. AVERAGE % REDUCTION IN
METAL LEACHING RESULTS FROM COPPER PIPE + 50/50 Pb-Sn SOLDER*

Treatment	Dissolved Pb	Dissolved Cu
Control	0	0
Lime	81.3	78.1
Lime + NaHCO ₃	84.4	76.4

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*Flow rate = 0.15 m/s.

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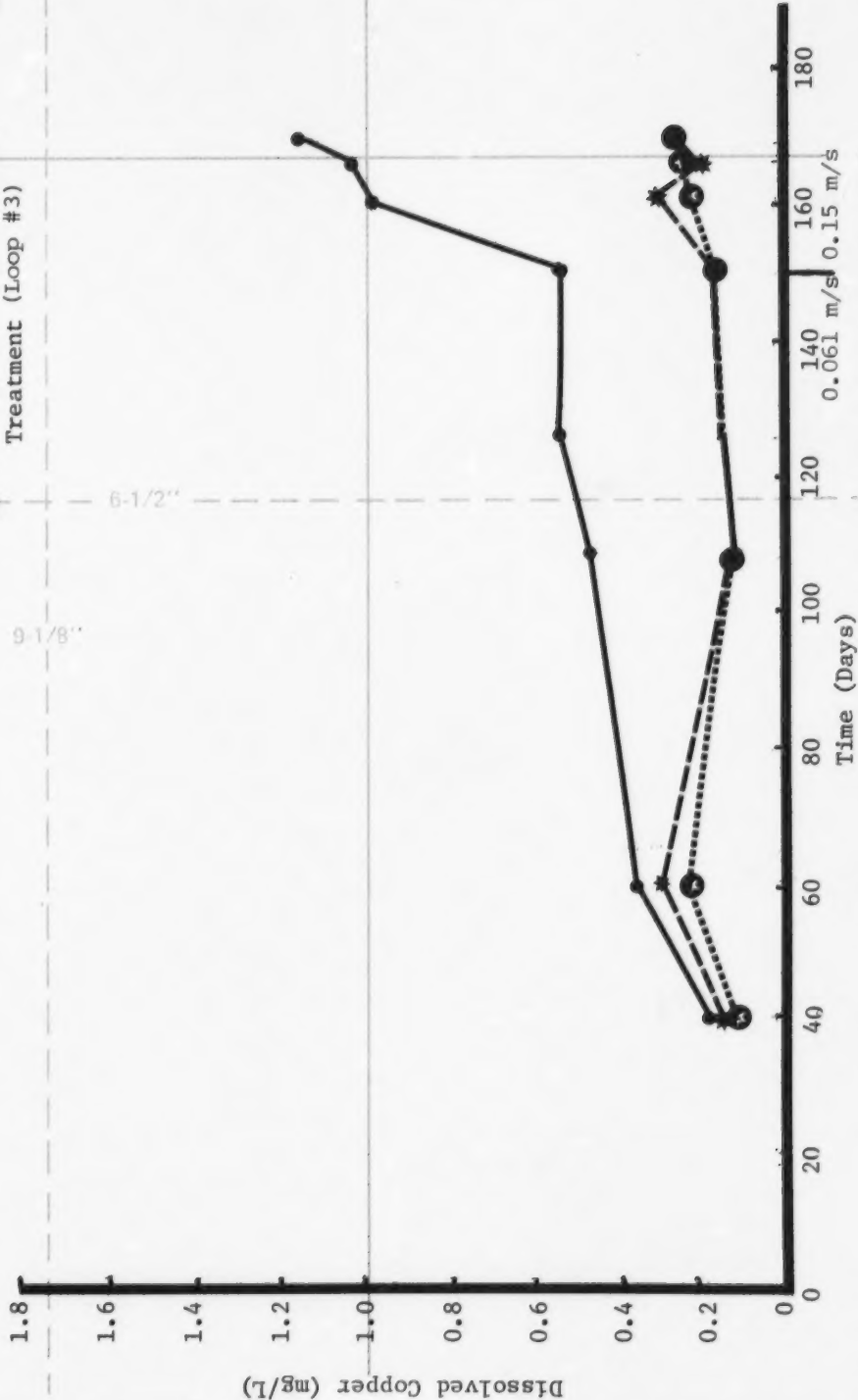


Figure 9. Cedar pilot plant test results - copper leaching from copper piping & 50/50 lead/tin solder.

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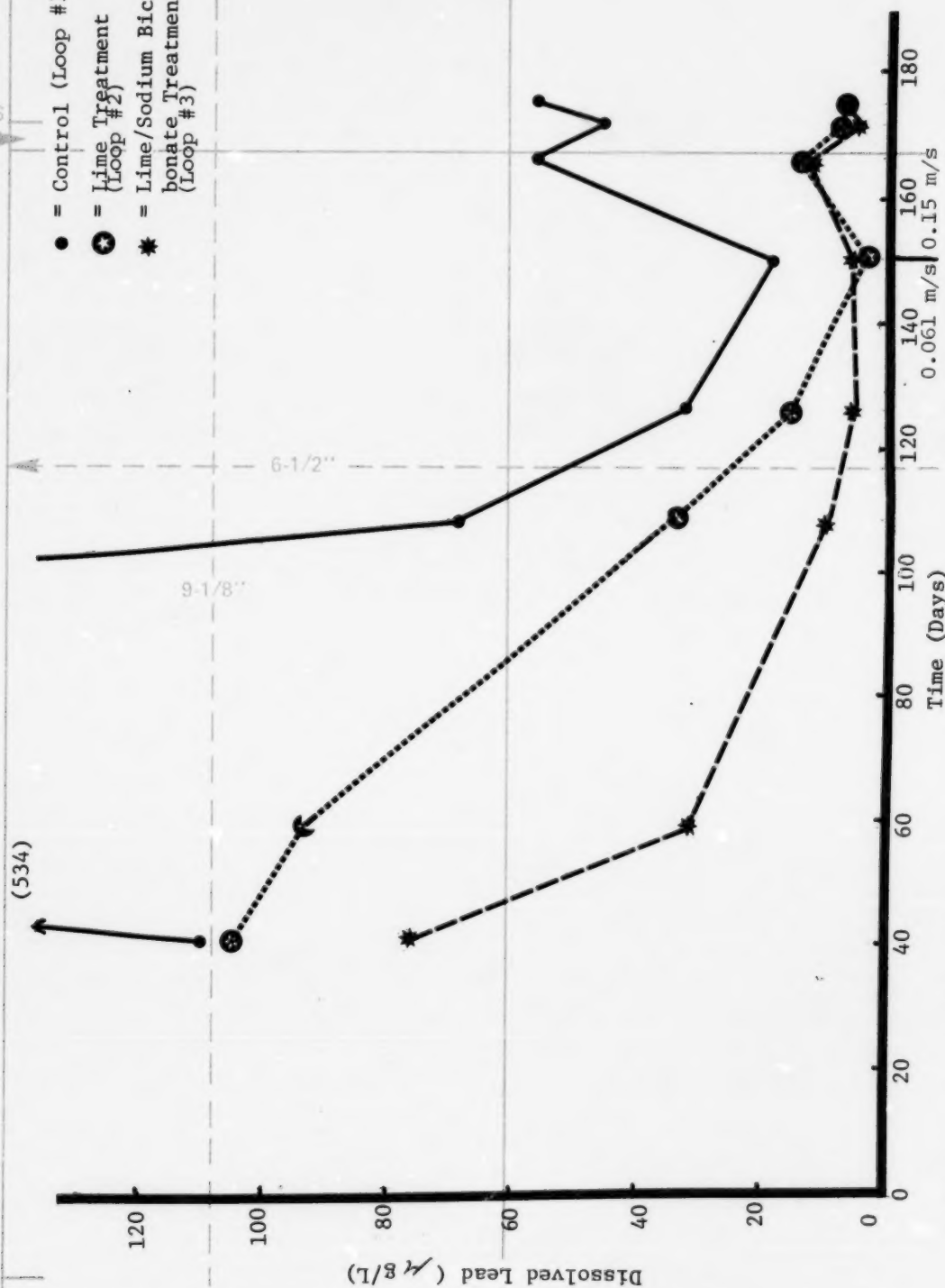


Figure 10. Cedar Pilot plant test results - lead leaching from copper piping with 50/50 lead/tin solder.

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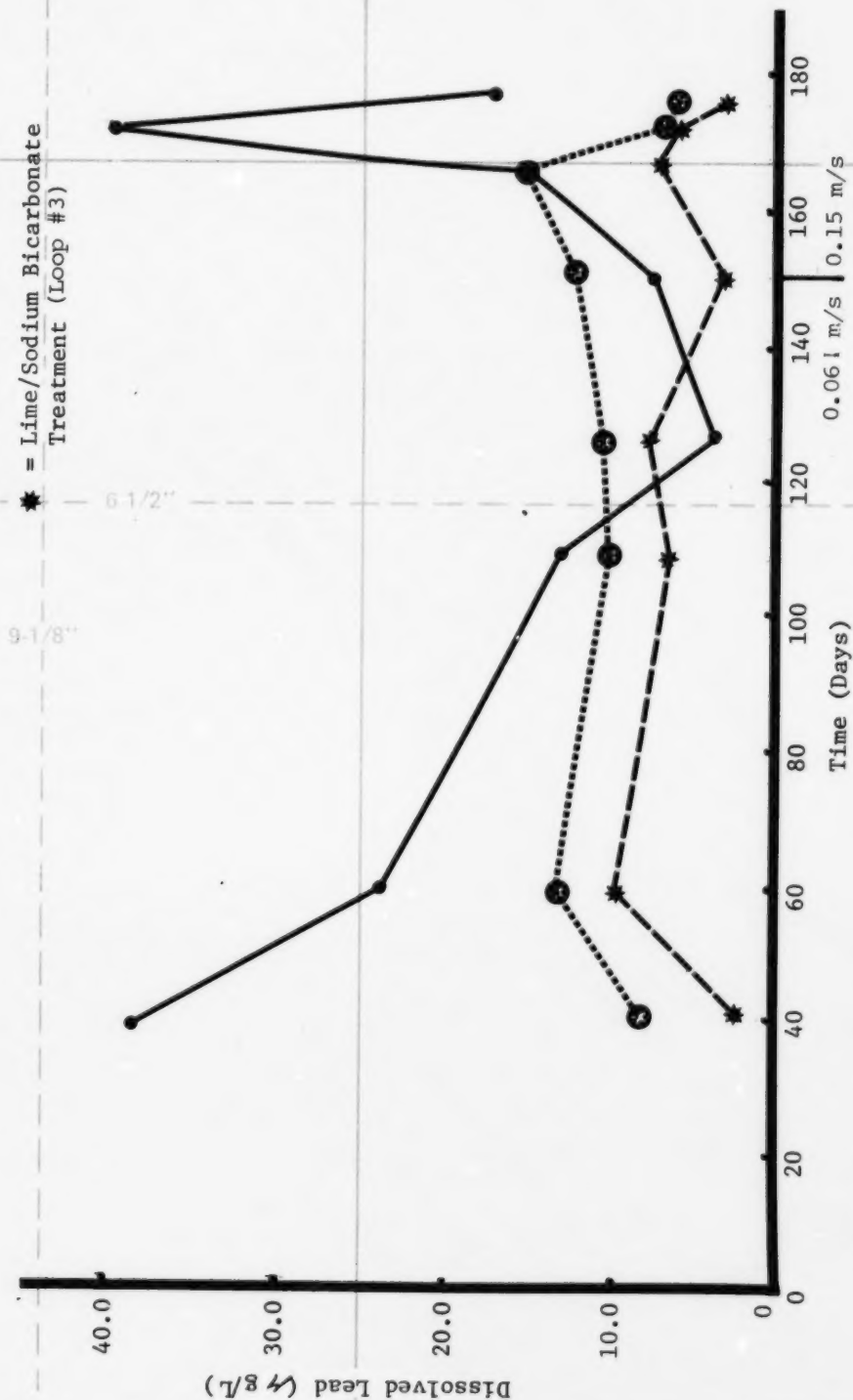


Figure 11. Cedar pilot plant test results - lead from galvanized steel piping.

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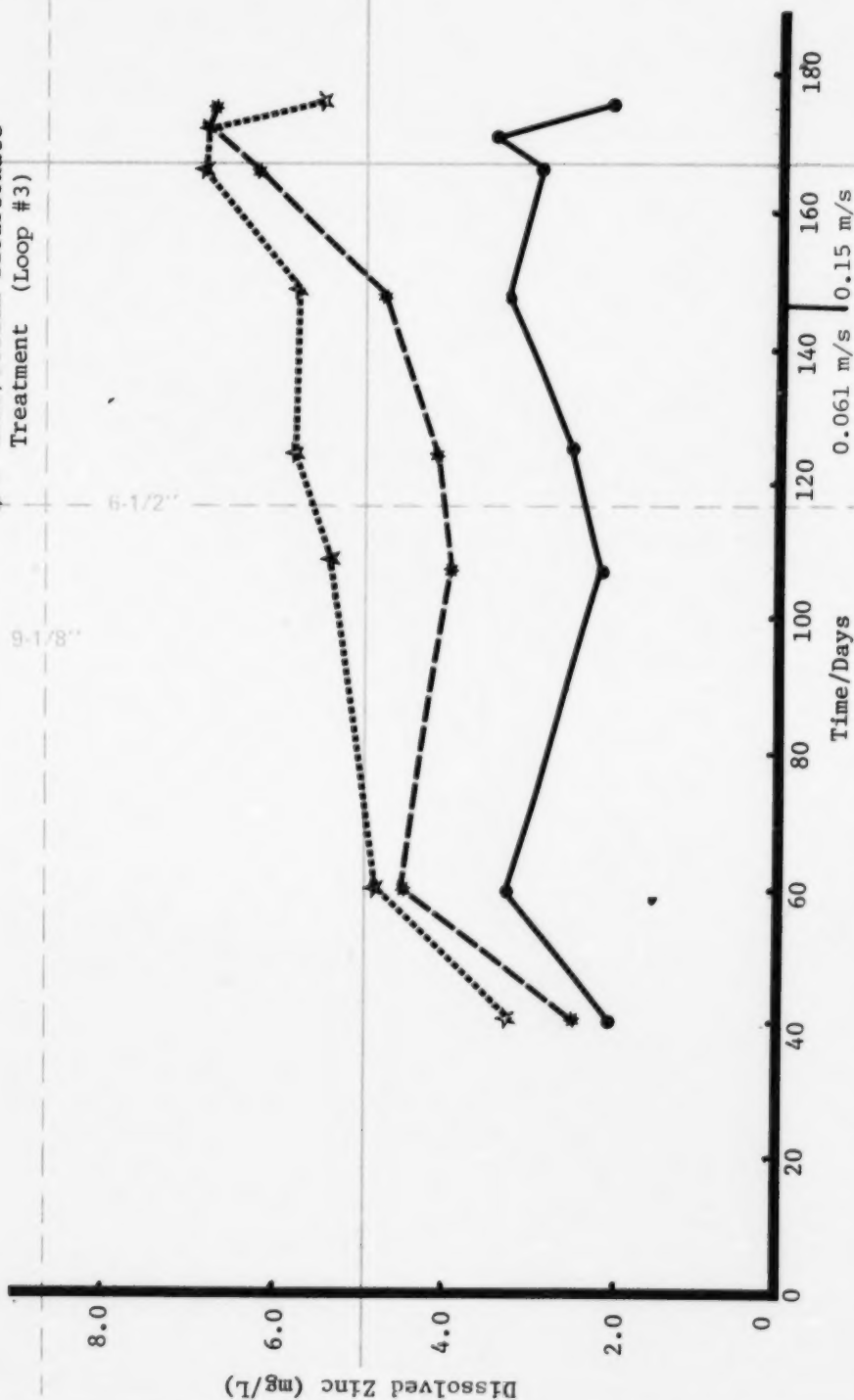


Figure 12. Cedar pilot plant test results - zinc leaching from galvanized steel piping.

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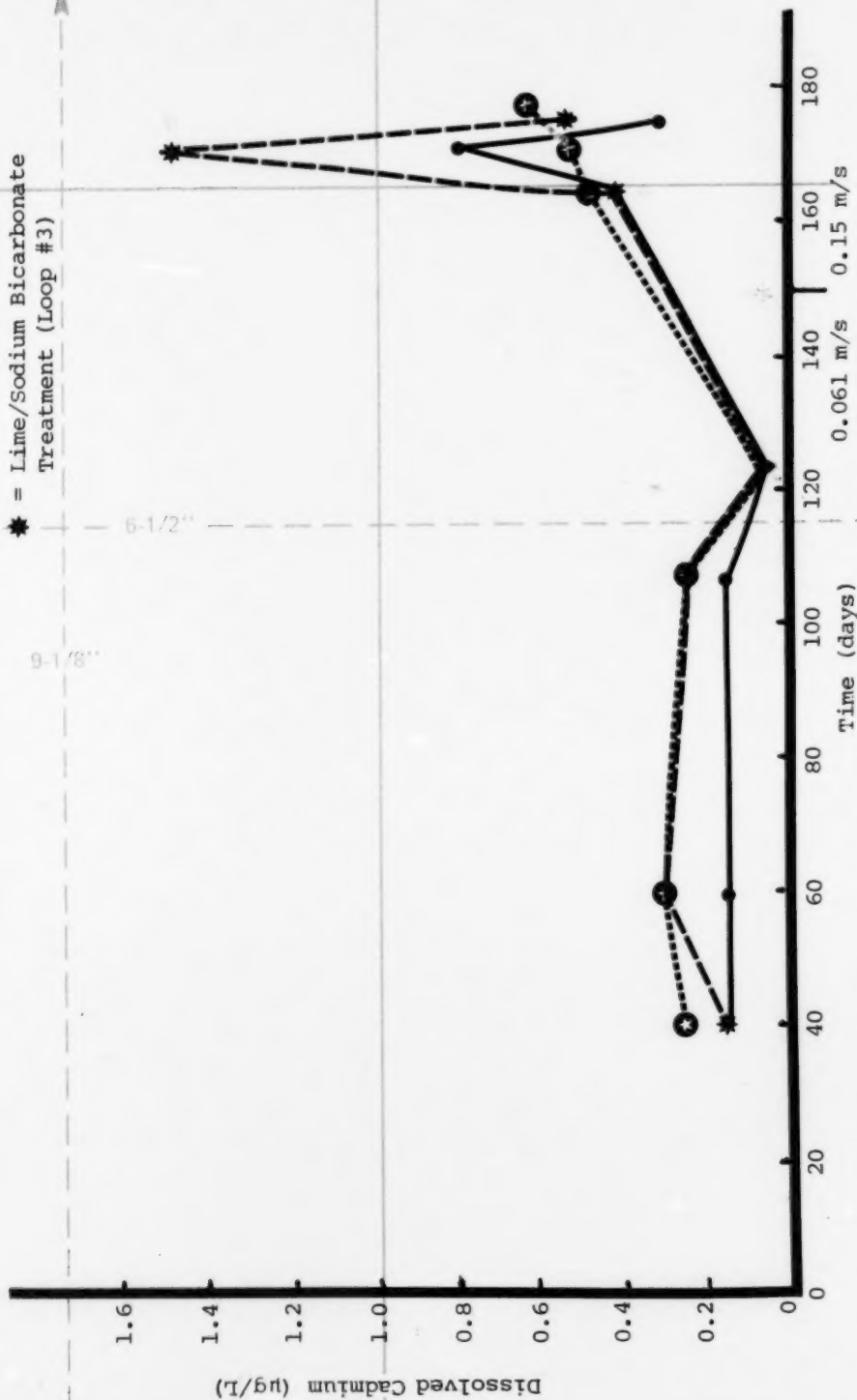


Figure 13. Cedar pilot plant test results - cadmium leaching from galvanized steel piping.

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TABLE 14. AVERAGE % REDUCTION IN
METAL LEACHING RESULTS FROM GALVANIZED STEEL PIPE*

	Pb		Zn		Cd
	Dissolved	Total	Dissolved	Total	Dissolved
Control, Loop #1	0	0	0	0	0
Lime, Loop #2	-49	-49	+138	+96	+32
Lime + NaHCO ₃ , Loop #3	-72	-54	+152	+176	+51

*Flow rate = 0.15 m/s.

CORROSION OF GALVANIZED PIPE IN STANDING CEDAR WATER

General

The results from the continuous flow coupon tests clearly demonstrated a reduction in corrosion rates with chemical treatment. By contrast, metal leaching tests showed an increase in galvanized pipe corrosion as a result of treatment. This section explains a possible mechanism for the increase in zinc and cadmium leaching from galvanized pipe in standing water as a result of chemical treatment.

Stability of Zinc Passivation Films

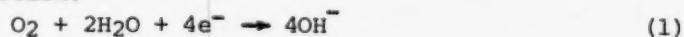
Figure 14 illustrates the stability domains of zinc species. This diagram, which is constructed from the equations in Table 15, is primarily an aid for the interpretation of equilibrium constants and provides an overview of the thermodynamically favorable reactions in the specific corroding system. As shown in Figure 14, in Cedar water a solid zinc species or passivation film, Zn(OH)₂ is stable between 7.95 and 11.65. This film has the capability of protecting metallic zinc and possibly metallic zinc and possibly metallic cadmium from corrosion. At pH greater than 11.65, the dissolved species HZnO₂⁻ and ZnO₂⁼ predominate, and at pH less than 7.95, Zn⁺⁺ predominates.

It should be noted that in Cedar water, protection by zinc carbonate (ZnCO₃) films is unlikely. In Cedar water, which has an alkalinity of only 15 mg/L CaCO₃, a dissolved zinc concentration greater than 75 mg/L is needed to stabilize ZnCO₃ with respect to Zn(OH)₂.

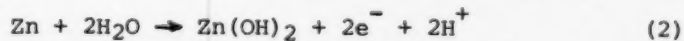
Localized Zinc Corrosion

Under the flowing conditions of the continuous flow coupon test unit, corrosion is uniform and a uniform passivation film is deposited. However, under the standing conditions of the metal leaching test, localized corrosion occurs, creating local pH differences and a non-uniform corrosion film.

At cathode zones, the reduction of dissolved oxygen takes place according to the following reaction:



thereby increasing pH in those zones. At the anode site, the principal oxidation reactions are:



for pH > 7.95, which can decrease pH at the anodic sites, and



for pH < 7.95.

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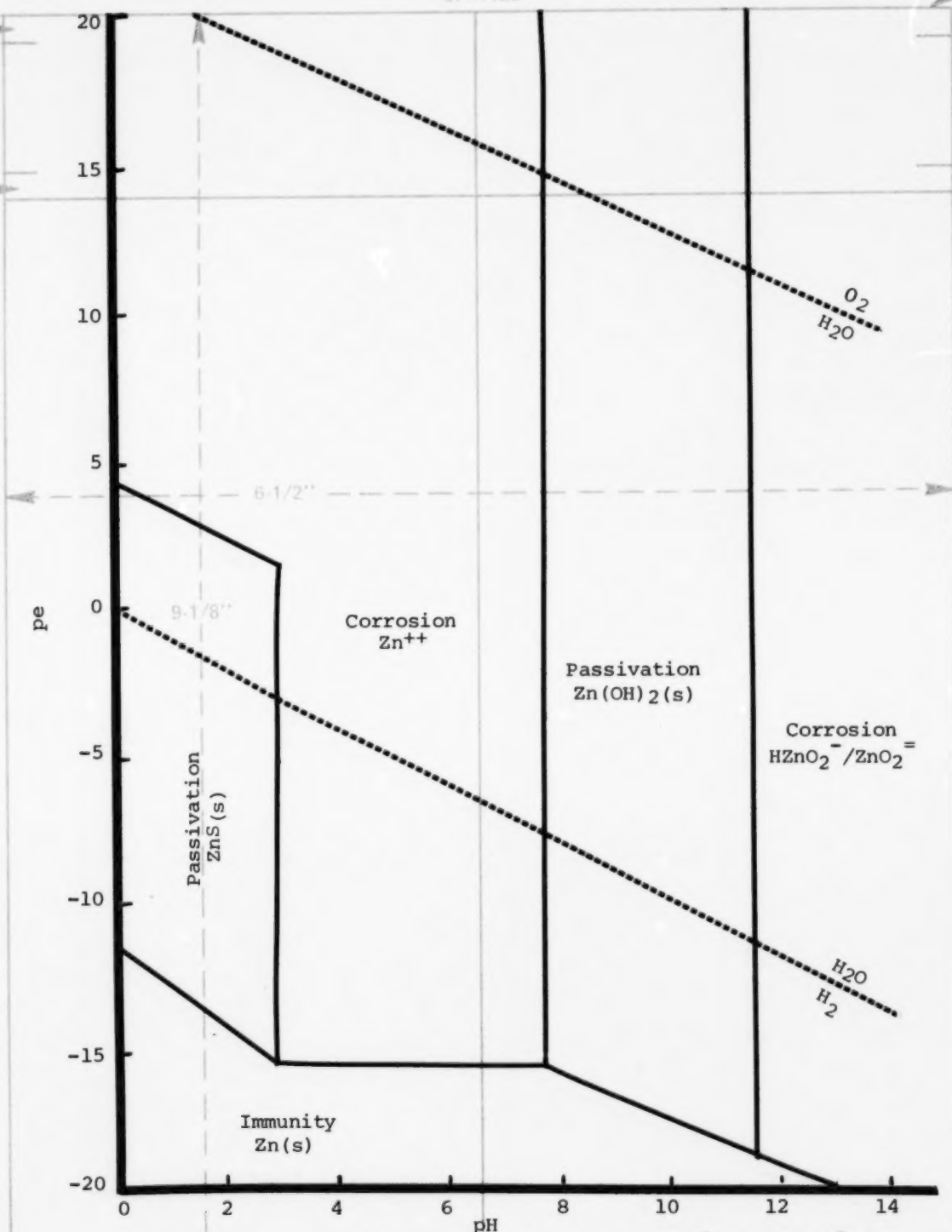


Figure 14. pe-pH diagram for zinc ($Zn(T) = 10^{-5} M$, $S_T = 10^{-5} M$, $C_T = 10^{-3.8} M$)

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TABLE 15. THERMODYNAMIC EQUATIONS FOR AQUEOUS CORROSION OF ZINC

(Zn - H₂O - S - C System)

Equation	log K*
1. $O_2(g) + 4H^+ + 4e^- = 2H_2O$ $pe = 20.8 - pH + 1/2 \log P_{O_2}$	83.2
2. $2H^+ + 2e^- = H_2(g)$ $pe = -pH - 1/2 \log P_{H_2}$	0
3. $Zn^{++} + H_2O = Zn(OH)^+ + H^+$ $pH = 0.66 + \log [Zn(OH)^+]/[Zn^{++}]$	-9.66
4. $Zn(OH)^+ + H_2O = HZnO_2^- + 2H^+$ $pH = 8.98 + 1/2 \log [HZnO_2^-]/[Zn(OH)^+]$	-17.95
5. $Zn^{++} + 2H_2O = HZnO_2^- + 3H^+$ $pH = 9.20 + 1/3 \log [HZnO_2^-]/[Zn^{++}]$	-27.61
6. $HZnO_2^- = ZnO_2^{=} + H^+$ $pH = 13.10 + \log [ZnO_2^{=}] / [HZnO_2^-]$	-13.10
7. $Zn + H_2S = ZnS + 2H^+ + 2e^-$ $pe = -15 - pH - 1/2 \log [H_2S]$	30.00
8. $Zn + 2H_2O = Zn(OH)_2 + 2e^- + 2H^+$ $pe = -7.43 - pH$	14.85
9. $Zn^{++} + H_2S = ZnS + 2H^+$ $pH = -2.08 - 1/2 \log [H_2S] - 1/2 \log [Zn^{++}]$	4.16

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Equation	log K*
10. $\text{Zn}^{++} + \text{HSO}_4^- + 7\text{H}^+ + 8\text{e}^- = \text{ZnS} + 4\text{H}_2\text{O}$ $\text{pe} = 5.92 - 7/8 \text{ pH} + 1/8 \log [\text{Zn}^{++}] + 1/8 \log [\text{HSO}_4^-]$	47.39
11. $\text{Zn}^{++} + \text{SO}_4^{=2-} + 8\text{H}^+ + 8\text{e}^- = \text{ZnS} + 4\text{H}_2\text{O}$ $\text{pe} = 5.65 - \text{pH} + 1/8 \log [\text{Zn}^{++}] + 1/8 \log [\text{SO}_4^{=2-}]$	45.19
12. $\text{Zn} = \text{Zn}^{++} + 2\text{e}^-$ $\text{pe} = -12.90 + 1/2 \log [\text{Zn}^{++}]$	25.79
13. $\text{Zn}^{++} + 2\text{H}_2\text{O} = \text{Zn}(\text{OH})_2 + 2\text{H}^+$ $\text{pH} = 5.48 - 1/2 \log [\text{Zn}^{++}]$	-10.95
14. $\text{Zn}(\text{OH})_2 = \text{HZnO}_2^- + \text{H}^+$ $\text{pH} = 16.66 + \log [\text{HZnO}_2^-]$	-16.66
15. $\text{Zn} + 2\text{H}_2\text{O} = \text{HZnO}_2^- + 3\text{H}^+ + 2\text{e}^-$ $\text{pe} = 0.91 - 3/2 \text{ pH} + 1/2 \log [\text{ZnO}_2^{=2-}]$	-1.82
16. $\text{Zn} + 2\text{H}_2\text{O} = \text{ZnO}_2^{=2-} + 4\text{H}^+ + 2\text{e}^-$ $\text{pe} = 7.46 - 2\text{pH} + 1/2 \log [\text{ZnO}_2^{=2-}]$	-14.92
17. $\text{Zn}^{++} + \text{HCO}_3^- = \text{ZnCO}_3 + \text{H}^+$ $\text{pH} = .51 - \log [\text{Zn}^{++}] - \log [\text{HCO}_3^-]$	-0.51
18. $\text{Zn}^{++} + \text{SO}_4^{=2-} = \text{ZnSO}_4$ $\log [\text{Zn}^{++}] + \log [\text{HCO}_3^-] = 3.09$	-3.09
19. $\text{H}_2\text{CO}_3 = \text{HCO}_3^- + \text{H}^+$ $\text{pH} = 6.38 + \log [\text{HCO}_3^-] / [\text{H}_2\text{CO}_3]$	-6.38

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Equation	log K*
20. $\text{HCO}_3^- = \text{CO}_3^{=} + \text{H}^+$ $\text{pH} = 10.34 - \log [\text{CO}_3^{=}] / [\text{HCO}_3^-]$	-10.34
21. $\text{H}_2\text{S} = \text{HS}^- + \text{H}^+$ $\text{pH} = 7.00 + \log [\text{HS}^-] / [\text{H}_2\text{S}]$	-7.00
22. $\text{HSO}_4^- = \text{SO}_4^{=} + \text{H}^+$ $\text{pH} = 1.91 + \log [\text{SO}_4^{=}] / [\text{HSO}_4^-]$	-1.91
23. $\text{H}_2\text{S} + 4\text{H}_2\text{O} = \text{HSO}_4^- + 9\text{H}^+ + 8\text{e}^-$ $\text{pe} = 4.89 - 1.13 \text{ pH} + \log [\text{HSO}_4^-] / [\text{H}_2\text{S}]$	-39.12
24. $\text{H}_2\text{S} + 4\text{H}_2\text{O} = \text{SO}_4^{=} + 10\text{H}^+ + 8\text{e}^-$ $\text{pe} = 5.13 - 1.25 \text{ pH} + \log [\text{SO}_4^{=}] / [\text{H}_2\text{S}]$	-41.03
25. $\text{HS}^- + 4\text{H}_2\text{O} = \text{SO}_4^{=} + 9\text{H}^+ + 8\text{e}^-$ $\text{pe} = 4.25 - 1.13 \text{ pH} + \log [\text{HS}^-] / [\text{SO}_4^{=}]$	-34.02

*Calculated from free energy data.¹³

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Standing Cedar Water (Present Quality)

In the case of Cedar water at its present pH of 7.2 standing in galvanized pipe, the pH is such that at the anodic sites, zinc readily dissolves according to equation #3 on page 34. At the cathodic sites there is a rise in pH due to the reduction of dissolved oxygen. The pH at the cathode is raised to such an extent that it falls within the stability domain of the $Zn(OH)_2$ passivation film. Localized corrosion, therefore, takes place where zinc can corrode at the anodic sites, limited by the degree of protection afforded the $Zn(OH)_2$ film at the cathode sites.

Standing Cedar Water (Treated)

When treated water stands in galvanized steel piping, local differences of pH again inevitably occur. The pH at the cathode is raised according to equation #1. However, since treated water has an initial pH of greater than 7.9, the pH increases at the cathode to such an extent that the passivation film is not stable (see Figure 14) and zinc can readily corrode. At the anode the pH decreases according to equation #2 until the $Zn(OH)_2$ film is no longer stable. Zinc can then corrode at the anode according to equation #3.

Summary

In standing treated water, the passivation film is unstable at both the anode and cathode, while in standing untreated water passivation can occur only at the cathode. There is, therefore, a greater area where the passivation film is not stable and corrosion can occur in standing water. As a result, zinc and cadmium leaching is more severe under standing treated water conditions than under standing untreated water conditions.

Corrosion rates under treated standing water conditions are therefore increased, while the corrosion rates, as measured in the continuous flow coupon tests, were reduced by treatment. Since the conditions in a premise plumbing system vary from standing to flowing, it is uncertain whether corrosion treatment will significantly increase the life span of new galvanized pipe.

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SECTION 7

BENEFITS OF TREATMENT

GENERAL

The treatment of Cedar water with either lime or lime/bicarbonate is expected to have a positive impact on the customer by means of improved water quality at the tap, aesthetic improvements, and economic benefits.

LIME VERSUS LIME/BICARBONATE

The addition of lime is usually the most economical method to increase pH and calcium in water. Sodium bicarbonate, which is used to increase the buffering capacity of the water, is considerably more expensive.

As demonstrated in the coupon and metal leaching tests, lime/bicarbonate treatment did not prove as effective as lime treatment and therefore should not be used.

A substantial savings is realized by eliminating bicarbonate treatment as demonstrated in Table 16.

BENEFITS OF TREATMENT

Changes in Water Quality

Lime treatment will raise the pH and thus reduce the corrosiveness of Cedar water. As a result, copper and lead levels in overnight standing tap

TABLE 16. SAVINGS REALIZED BY ELIMINATING FEEDING OF 6.0 mg/L NaHCO_3

Item	Amount/yr
Chemicals	\$201,000*
Capital Facilities (20 years @ 7%)	17,200†
Labor, Maintenance, Power	6,300†
	\$224,500

*Based on cost of sodium bicarbonate delivered at Lake Youngs, June 1981.

†1981 cost estimate based on Kennedy Engineers⁴ Phase III report, and assigning a conservative 22% factor attributable to bicarbonate system capital facilities, labor, maintenance, and power.

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water will be substantially reduced. Also expected is a reduction in the percentage of samples which exceed the MCL for these metals. Only small reductions of zinc, cadmium and iron levels in overnight standing water are expected.

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Aesthetic Impact

Complaints of red water and metallic taste and odor should decrease following treatment. The customer will also benefit from the reduction of red and blue fixture and clothing stains caused by the corrosion of galvanized and copper pipe.

Economic Benefits

The expected percent reductions in corrosion rates resulting from lime treatment are expected to significantly increase the service life of premise plumbing in the Cedar service area. Copper pipe service life is expected to increase by 65%. Galvanized steel pipe service life is also expected to increase, but the amount of increase is uncertain. The longer service life implies a reduction in plumbing replacement and maintenance costs. Additional cost savings include a reduction in distribution system maintenance cost, and costs associated with responding to corrosion-related water quality complaints within the City of Seattle and the suburban water agencies. A detailed analysis of the economic benefits of treatment can be found in the Seattle Internal Corrosion Study.⁴

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APPENDIX A

CEDAR pH STABILITY TESTS

TEST OBJECTIVES

The objective of these tests was to determine the pH conditions under which the pilot studies should be conducted. This is based on the maximum pH depression in the Cedar distribution system and the pH stability of lime, sodium carbonate (soda ash) and lime/sodium bicarbonate corrosion control treatments.

CONCLUSIONS

Pilot testing should be conducted with lime and lime/sodium bicarbonate treatments. Testing of soda ash treatment is not necessary because this treatment produces a water quality between that of lime and lime/sodium bicarbonate treatment.

Pilot tests comparing lime treatment to lime plus bicarbonate treatment should maintain a 0.02 to 0.04 pH difference to simulate the average differences that would effect pipeline-served customers (0.00 pH difference) and reservoir-served customers (0.02 to 0.04 pH difference). The pilot test conditions should also maintain pH between the treatment plant level (8.3) and the minimum distribution level (7.6 to 7.65) to best simulate the average condition.

PROCEDURE

A 3.8 liter sample of Cedar pipeline water was collected and immediately analyzed for pH, total alkalinity, and °C. Based on the calculated CO₂ level, the dosages of lime and soda ash to convert all CO₂ to bicarbonate were then calculated. 800 ml aliquots of the sample were treated with lime and soda ash to 0.0 mg/L CO₂ using a pH meter to confirm the end point. Additionally, one lime-treated aliquot was also treated with 6 mg/L NaHCO₃. The four aliquots (no treatment; lime; soda ash; lime + NaHCO₃) were stirred on a jar test apparatus at 12 revolutions per minute (RPM) for 24 hours and pH measurements were taken five times. After stabilization testing was over, each sample was treated with chlorine injector water to give a 0.4 mg/L residual. pH readings were then taken immediately.

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RESULTS

The Cedar pipeline water quality is presented in Table A-1.

From the data presented in Table A-1, the lime and soda ash dosages presented in Table A-2 were chosen.

The stabilization and rechlorination tests were then performed to determine the pH depression. The results are summarized in Table A-3.

TABLE A-1. CEDAR PIPELINE WATER QUALITY

Parameter	Value
pH	7.22
Total Alkalinity (mg/L CaCO ₃)	14.2
Temperature (°C)	17.0
CO ₂ (mg/L)	1.90*

*By calculation.

TABLE A-2. TREATMENT DOSAGES

Treatment	Dosage (mg/L)	Final pH
Control	-	7.22
Lime	1.9 Ca(OH) ₂	8.12
Soda Ash	5.0 Na ₂ CO ₃	8.20
Lime/Bicarbonate	1.57 Ca(OH) ₂ + 6.0 NaHCO ₃	8.12

TABLE A-3. pH DEPRESSION TEST RESULTS

Treatment	Predicted Equilibrium pH @ 25°C	pH After Stabilization @ 22°C	pH After Chlorination	Alkalinity After Stabilization mg/L CaCO ₃
Control	7.60	7.73	7.49	14.2
Lime	7.69	7.80	7.60	16.6
Soda Ash	7.73	7.85	7.63	18.5
Lime/Bicarbonate	7.72	7.87	7.64	19.6

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APPENDIX B. QUALITY CONTROL DATA

TABLE B-1. COUPON QUALITY CONTROL DATA (Summarized by Each Coupon)

		Days Exposure	Average pH*	pH Range	Standard Deviation	Average Flow
Loop #1						
Copper	#1	15	7.23	7.21-7.26	.014	.148
	#2	53	7.28	7.21-7.37	.032	.149
	#3	140	7.32	7.20-7.49	.037	.170
	#4	176	7.31	7.19-7.49	.035	.173
Iron	#1	47	7.28	7.21-7.37	.032	.149
	#2	134	7.32	7.20-7.49	.037	.170
	#3	170	7.31	7.19-7.49	.035	.173
	#4	193	7.30	7.13-7.49	.040	.176
Galvanized	#1	47	7.28	7.21-7.37	.032	.149
	#2	134	7.32	7.20-7.49	.037	.170
	#3	170	7.31	7.19-7.49	.035	.173
	#4	193	7.30	7.13-7.49	.040	.176
Loop #2						
Copper	#1	15	7.84	7.66-7.99	.081	.143
	#2	53	7.88	7.66-8.21	.093	.143
	#3	140	7.87	7.36-8.24	.126	.149
	#4	176	7.87	7.36-8.24	.121	.148
Iron	#1	47	7.88	7.66-8.21	.093	.143
	#2	134	7.87	7.36-8.24	.126	.149
	#3	170	7.87	7.36-8.24	.121	.148
	#4	193	7.87	7.36-8.24	.114	.148
Galvanized	#1	47	7.88	7.66-8.21	.093	.143
	#2	134	7.87	7.36-8.24	.126	.149
	#3	170	7.87	7.36-8.24	.121	.148
	#4	193	7.87	7.36-8.24	.114	.148
Loop #3						
Copper	#1	15	7.93	7.75-8.01	.074	.159
	#2	53	7.94	7.75-8.30	.090	.155
	#3	140	7.93	7.39-8.30	.114	.159
	#4	176	7.92	7.39-8.30	.115	.158
Iron	#1	47	7.94	7.75-8.30	.090	.155
	#2	134	7.93	7.39-8.30	.114	.159
	#3	170	7.92	7.39-8.30	.115	.159
	#4	193	7.92	7.39-8.30	.109	.158
Galvanized	#1	47	7.94	7.75-8.30	.090	.155
	#2	134	7.93	7.39-8.30	.114	.159
	#3	170	7.92	7.39-8.30	.115	.159
	#4	193	7.92	7.39-8.30	.109	.158

*Based on daily $[H^+]$ x hrs. exposure, averaged over each coupon's exposure period.

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TABLE B-2. TEST LOOP QUALITY CONTROL (SUMMARIZED IN 2- TO 4-WEEK PERIODS)

Time Interval	Loop #1 Control				Loop #2 Lime				Loop #3 Lime + Sodium Bicarbonate					Δ Alk. via NaHCO ₃ (mg/L)
	Average pH	pH Range	Standard Deviation	Average Flow (L/sec)	Average pH	pH Range	Standard Deviation	Average Flow (L/sec)	Average pH	pH Range	Standard Deviation	Average Flow (L/sec)	Total Alk. (mg/L)	
6/2-6/21	7.24	7.21-7.27	.017	.151	7.86	7.66-8.21	.104	.143	7.94	7.75-8.30	.102	.159	20.3	3.9
6/22-7/9	7.28	7.21-7.35	.045	.148	7.89	7.74-8.04	.102	.143	7.92	7.75-8.08	.107	.154	20.5	3.7
7/10-7/24	7.33	7.25-7.37	.033	.149	7.91	7.84-8.09	.074	.143	7.96	7.89-8.14	.060	.153	21.95	3.4
7/25-8/13	7.39	7.31-7.49	.054	.174	7.96	7.81-8.24	.102	.151	8.00	7.83-8.24	.102	.160	23.0	3.0
8/13-8/31	7.42	7.38-7.49	.029	.188	7.93	7.84-8.03	.124	.152	7.98	7.80-8.21	.109	.161	24.4	4.0
8/31-9/14	7.39	7.36-7.41	.016	.182	7.79	7.36-8.10	.230	.153	7.89	7.64-8.13	.161	.162	24.4	3.5
9/15-10/3	7.31	7.28-7.37	.040	.186	7.89	7.84-8.07	.128	.152	7.93	7.71-8.10	.114	.160	25.8	4.4
10/4-10/23	7.25	7.30-7.37	.058	.186	7.75	7.48-8.00	.142	.152	7.82	7.39-8.09	.155	.162	25.6	3.6
10/24-11/20	7.26	7.19-7.37	.038	.189	7.85	7.72-8.04	.083	.148	7.88	7.74-8.09	.109	.160	24.9	3.6
11/21-12/4	7.26	7.13-7.34	.063	.189	7.88	7.71-8.02	.101	.145	7.86	7.61-8.05	.133	.160	-	-
12/5-12/18	7.31	7.21-7.38	.043	.189	7.90	7.81-8.06	.061	.146	7.96	7.91-8.08	.046	.149	21.9	4.2
6/2/-12/18	7.30	7.13-7.49	.040	.176	7.87	7.36-8.24	.114	.148	7.92	7.39-8.30	.109	.158	23.3	3.72*

*Equivalent to 6.25 mg/L NaHCO₃.

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TABLE B-3. CALCULATED LIME DOSAGE BASED ON PERIODIC CHEMICAL ANALYSIS

		Loop #1	Loop #2	Loop #3
6/17	pH	7.17	7.79	7.92
	Total Alkalinity (mg/L CaCO ₃)	14.3	16.2	20.0
	Ca (mg/L CaCO ₃)	15.3	17.4	18.3
	Specific Conductance, μ mhos	49.1	52.2	59.1
	CaO dosage, mg/L	-	1.1	1.4
6/21	pH	7.27	7.97	8.01
	Total Alkalinity (mg/L CaCO ₃)	14.1	16.2	19.2
	Ca (mg/L CaCO ₃)	15.6	17.7	18.0
	Specific Conductance, μ mhos	48.5	52.	57.
	CaO dosage, mg/L	-	1.2	1.35
7/10	pH	7.28	7.89	7.93
	Total Alkalinity (mg/L CaCO ₃)	15.8	17.8	20.7
	Ca (mg/L CaCO ₃)	16.8	19.4	19.9
	Specific Conductance, μ mhos	52.0	55.5	60.6
	CaO dosage, mg/L	-	1.3	1.4
7/24	pH	7.38	7.98	8.03
	Total Alkalinity (mg/L CaCO ₃)	17.3	18.7	23.0
	Ca (mg/L CaCO ₃)	18.0	19.5	20.2
	Specific Conductance, μ mhos	53.5	58.3	65.3
	CaO dosage, mg/L	-	.8	1.25
8/13	pH	7.51	7.93	7.97
	Total Alkalinity (mg/L CaCO ₃)	17.6	19.6	23.2
	Ca (mg/L CaCO ₃)	18.4	20.4	20.8
	Specific Conductance, μ mhos	58.2	60.7	67.6
	CaO dosage, mg/L	-	1.1	1.35
10/23	pH	7.28	7.89	7.92
	Total Alkalinity (mg/L CaCO ₃)	19.6	21.7	26.0
	Ca (mg/L CaCO ₃)	19.8	22.2	22.6
	Specific Conductance, μ mhos	62.9	65.2	72.6
	CaO dosage, mg/L	-	1.25	1.5
11/20	pH	7.25	7.87	7.90
	Total Alkalinity (mg/L CaCO ₃)	18.8	21.2	24.5
	Ca (mg/L CaCO ₃)	20.6	23.0	-
	Specific Conductance, μ mhos	60.4	63.8	69.5
	CaO dosage, mg/L	-	1.35	1.55
12/10	pH	7.34	7.82	7.88
	Total Alkalinity (mg/L CaCO ₃)	17.5	20.1	23.3
	Ca (mg/L CaCO ₃)	18.9	21.6	22.0
	Specific Conductance, μ mhos	59.4	64.7	70.6
	CaO dosage, mg/L	-	1.5	1.75

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		<u>Loop #1</u>	<u>Loop #2</u>	<u>Loop #3</u>
12/16	pH	7.34	7.92	7.95
	Total Alkalinity (mg/L CaCO ₃)	17.1	19.7	23.0
	Ca (mg/L CaCO ₃)	19.2	22.4	22.2
	Specific Conductance, μ mhos	58.5	63.0	69.2
	CaO dosage, mg/L	-	1.6	1.55
12/19	pH	7.3	7.90	7.98
	Total Alkalinity (mg/L CaCO ₃)	16.5	19.0	21.9
	Ca (mg/L CaCO ₃)	19.3	21.7	21.4
	Specific Conductance, μ mhos	58.2	62.4	68.8
	CaO dosage, mg/L	-	1.35	1.4

Summary

Total Alkalinity (mg/L CaCO ₃)	16.86	19.02	22.26
Ca (mg/L CaCO ₃)	18.19	20.53	20.60
Specific Conductance, μ mhos	56.07	59.78	66.02
Calc. CaO dosage, mg/L	-	1.26	1.45
Calc. NaHCO ₃ dosage, mg/L*	-	-	6.25

*Based on weekly data, see Table B-2.

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TABLE B-4. METAL LEACHING TEST SECTIONS - FLOW AND VELOCITY SUMMARIZATION AND CALCULATIONS

Period*	Flow (L/sec)			Velocity in Copper Pipe (m/min)			Velocity over Solder in Copper Pipe (m/min)			Velocity in Galvanized Pipe (m/min)		
	Loop #1	Loop #2	Loop #3	Loop #1	Loop #2	Loop #3	Loop #1	Loop #2	Loop #3	Loop #1	Loop #2	Loop #3
6/9 - 6/20	5.33×10^{-5}	5.10×10^{-5}	4.72×10^{-5}	3.84	3.66	3.48	4.57	4.39	4.21	3.11	2.93	2.74
6/26 - 7/24	5.43×10^{-5}	5.14×10^{-5}	5.19×10^{-5}	4.02	3.84	3.84	4.76	4.57	4.57	3.11	2.93	3.11
7/26 - 8/13	5.62×10^{-5}	5.05×10^{-5}	5.33×10^{-5}	4.02	3.66	3.84	4.94	4.39	4.57	3.29	2.93	3.11
8/15 - 10/3	5.38×10^{-5}	5.47×10^{-5}	5.43×10^{-5}	4.02	4.02	4.02	4.76	4.76	4.76	3.11	3.11	3.11
10/5 - 10/23	5.29×10^{-5}	5.14×10^{-5}	5.14×10^{-5}	3.84	3.84	3.84	4.57	4.57	4.57	3.11	2.93	2.93
10/24-11/20	5.57×10^{-5}	5.33×10^{-5}	5.52×10^{-5}	4.02	3.84	4.02	4.94	4.57	4.76	3.29	3.11	3.29
11/25-12/10	1.41×10^{-4}	1.37×10^{-4}	1.42×10^{-4}	10.24	10.06	10.43	12.07	11.89	12.49	8.05	8.05	8.23
12/11-12/16	1.34×10^{-4}	1.41×10^{-4}	1.31×10^{-4}	9.69	10.24	9.51	11.71	12.25	11.34	7.68	8.23	7.68

*Summarized for each period proceeding leaching tests (based on daily flow readings).

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METAL LEACHING TEST SECTIONS FLOW AND VELOCITY SUMMARIZATION AND CALCULATIONS

Copper inside diameter = .792 cm

Diameter of solder = .318 cm

$$\text{Area of flow} = \frac{\pi (.792)^2}{4} - \frac{\pi (.318)^2}{4} = .413 \text{ cm}^2$$

$$Q = \left[\frac{200 \text{ mL}}{\text{min}} \right] \left[\frac{\text{L}}{1000 \text{ mL}} \right] \left[\frac{\text{min}}{60 \text{ sec}} \right]$$

$$Q = 3.0 \times 10^{-3}$$

$$V = \frac{Q}{A} = \frac{3.0 \times 10^{-3} \text{ L/sec}}{(.413 \text{ cm}^2)} \left[\frac{10^3 \text{ cm}^3}{\text{L}} \right]$$

V = 7.264 cm/sec at low flow

$$Q = \left[\frac{100 \text{ mL}}{12 \text{ sec}} \right] \left[\frac{\text{L}}{1000 \text{ mL}} \right]$$

$$Q = 8.0 \times 10^{-3} \text{ L/sec}$$

$$V = \frac{Q}{A} = \frac{8.0 \times 10^{-3} \text{ L/sec}}{(.413 \text{ cm}^2)} \left[\frac{10^3 \text{ cm}^3}{\text{L}} \right]$$

V = 19.37 cm/sec at high flow

Galvanized inside diameter = .889 cm

$$\text{Area of flow} = \frac{\pi (.889)^2}{4} = .621 \text{ cm}^2$$

$$V = \frac{Q}{A} = \frac{3.0 \times 10^{-3} \text{ L/sec}}{(.621 \text{ cm}^2)} \left[\frac{10^3 \text{ cm}^3}{\text{L}} \right]$$

V = 4.831 cm/sec at low flow

$$V = \frac{Q}{A} = \frac{8.0 \times 10^{-3} \text{ L/sec}}{(.621 \text{ cm}^2)} \left[\frac{10^3 \text{ cm}^3}{\text{L}} \right]$$

V = 1.288 x 10' cm/sec at high flow

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WATER METER CALIBRATIONS

December 1979

Loop #1 (Control)

19.65 liter container filled and timed:

1) 110 sec. 2) 109 sec. 3) 109 sec.

Average - 109.33 sec.

Loop #2 (Lime)

19.65 liter container filled and timed:

1) 136 sec. 2) 135 sec. 3) 135 sec.

Average - 135.33 sec.

Loop #3 (Lime + Bicarbonate)

19.65 liter container filled and timed:

1) 127 sec. 2) 128 sec. 3) 127 sec.

Average - 127.33 sec.

19.65 liters = 0.694 ft³

WATER METER READINGS

Loop #1 = 0.381 ft³/min.

#2 = 0.308 ft³/min.

#3 = 0.327 ft³/min.

Flow Correction Factors

Loop #1 was unmetered after 7/26/79 because the meter had a broken component and so volume/time measurements were made using a calibrated gallon container. From this point on, flows were adjusted to .5 gal/10 sec. which is equivalent to .4 ft³/min. due to an error in converting gallons/sec. to ft³/min. Ideally the flow rate should have been set at .33 ft³/min. to attain a velocity of 1 ft/sec past the coupons. The Loop #1 flow summary was based on the early meter readings (uncorrected) and the later gal/sec. readings.

Loop #2 actual flow/meter indicated flow = $\frac{0.308 \text{ ft}^3/\text{min.}}{0.322} = 0.956$

The Loop #2 flow summary was based on meter readings multiplied times the correction factor 0.956.

Loop #3 actual flow/meter indicated flow = $\frac{0.327 \text{ ft}^3/\text{min.}}{0.318} = 1.028$

The Loop #3 flow summary was based on meter readings multiplied times the correction factor 1.028.

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APPENDIX C. IRON PITTING ANALYSIS RESULTS

Exposure, Days	Test Loop #	Iron Corrosion Type	% Surface Attacked	Avg. Pit Depth, mils	Max. Pit Depth, mils	Pit Depth, Penetration Rate, mpy
47	1	General uneven & semi-local uneven	45	7.4	9.0	57.2
	2	Semi-local even	30	4.5	5.0	34.9
	3	Semi-local even	30	6.3	10.0	49.2
134	1	Semi-local uneven & wide pits	65	10.2	17.0	27.7
	2	Semi-local uneven & wide pits	45	14.0	19.0	38.1
	3	Semi-local uneven	45	9.3	14.0	25.4
170	1	Semi-local uneven & wide pits	60	14.6	18.0	31.3
	2	Semi-local uneven & wide pits	45	13.3	19.0	28.6
	3	Semi-local uneven & wide pits	55	11.3	16.0	24.2
193	1	Semi-local uneven & wide pits	70	11.6	18.0	22.0
	2	Semi-local uneven & wide pits	50	11.5	15.0	21.7
	3	Semi-local uneven & wide pits	70	12.0	15.0	22.7

*Based on average of 10 deepest pits, each coupon.

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APPENDIX D

PHOTOGRAPHS OF PILOT PLANT APPARATUS

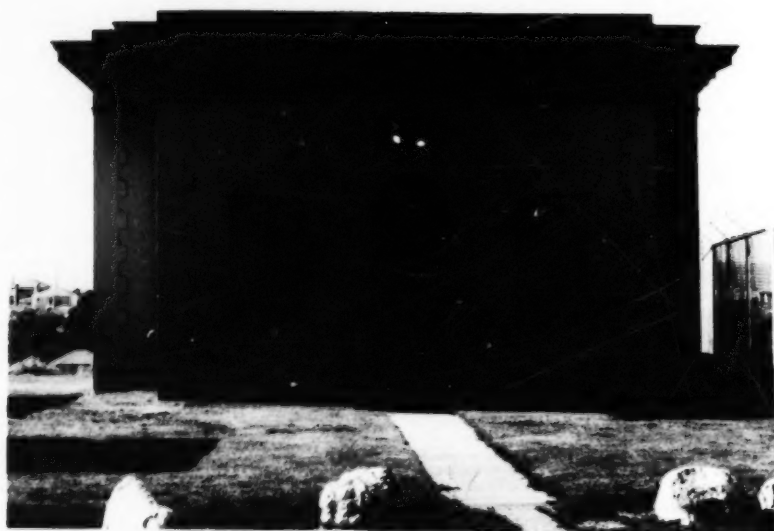


Figure D-1. Beacon Reservoir gate house.

Note: Pilot plant located inside this structure.

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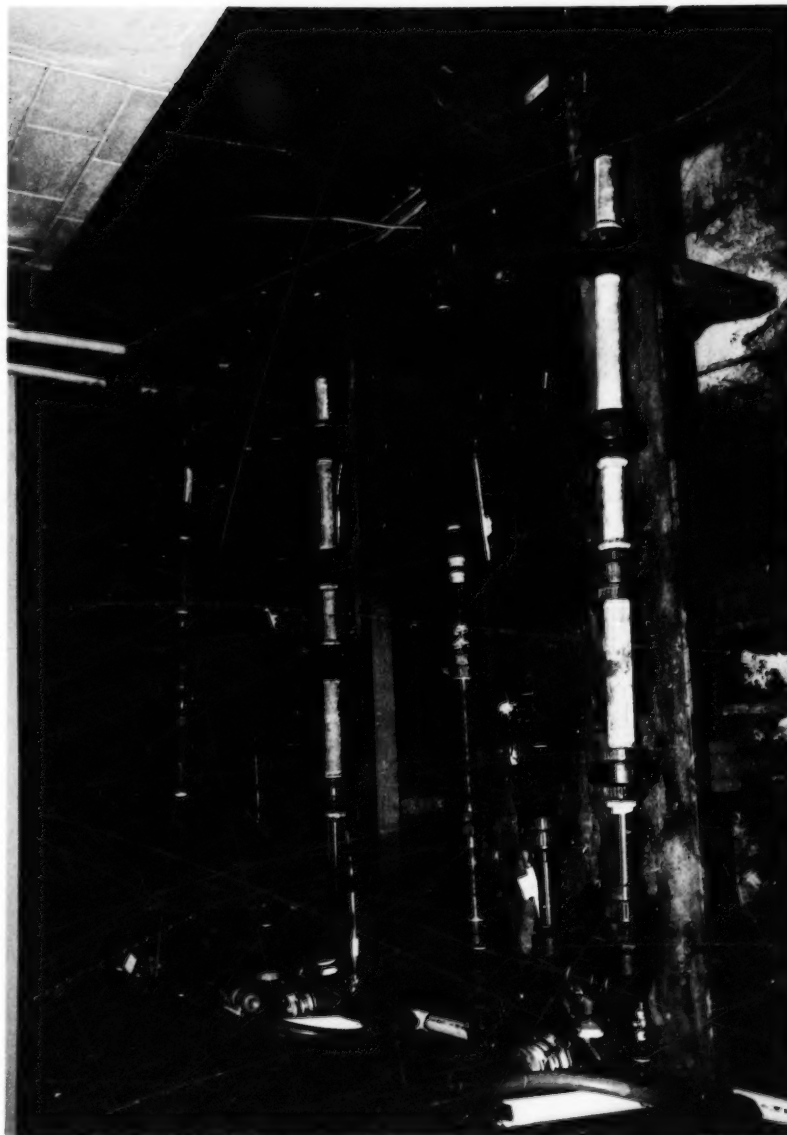


Figure D-2. Control, lime and lime/sodium bicarbonate treatment test loops.

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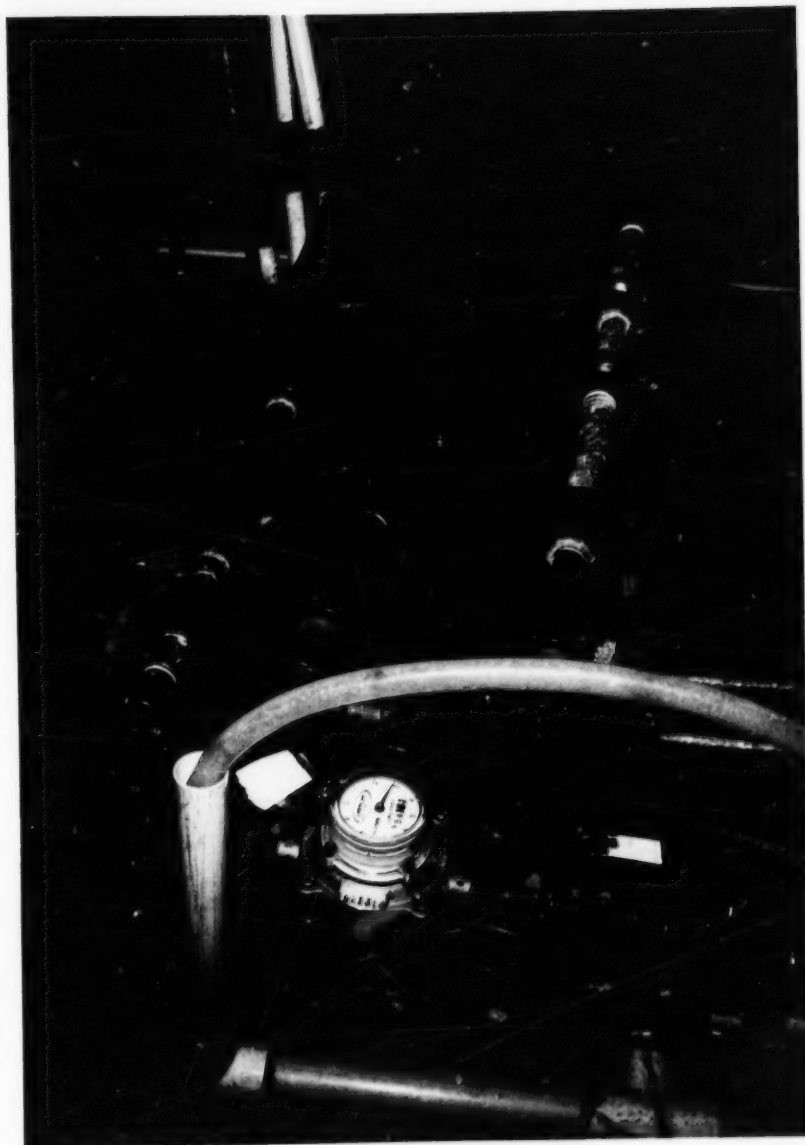


Figure D-3. ISWS continuous flow test loop.

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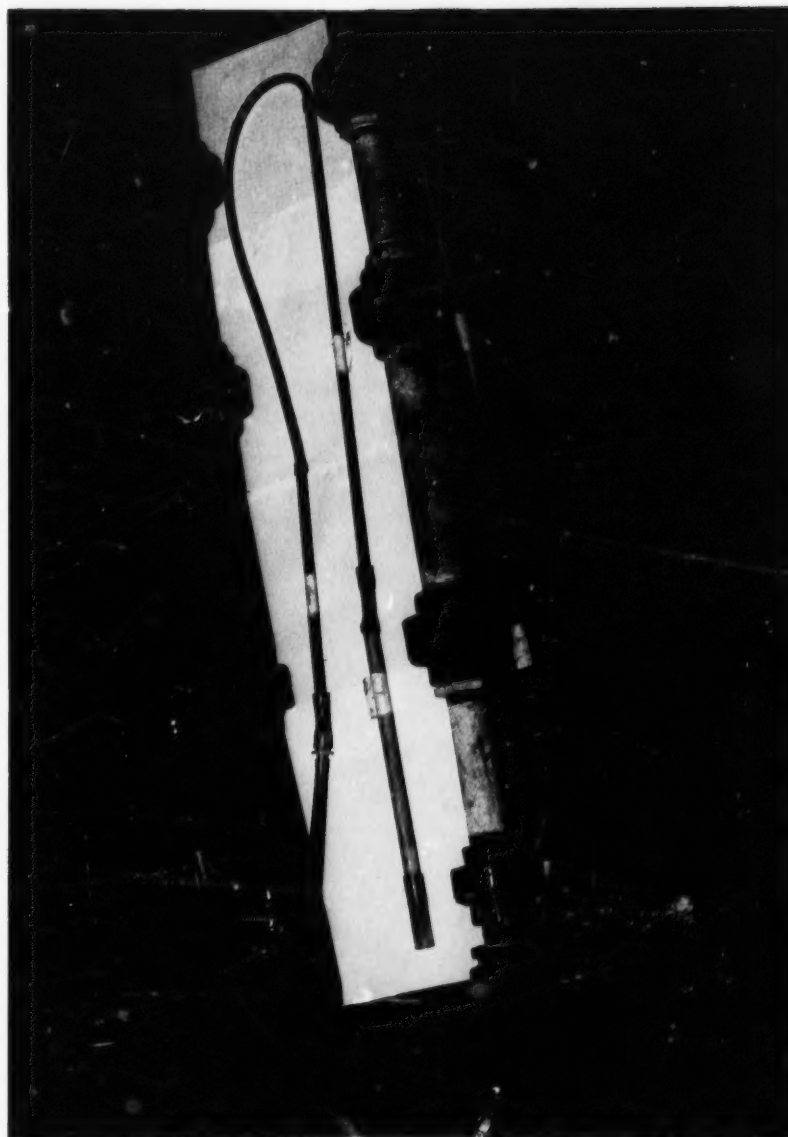


Figure D-4. Metal leaching test loop.

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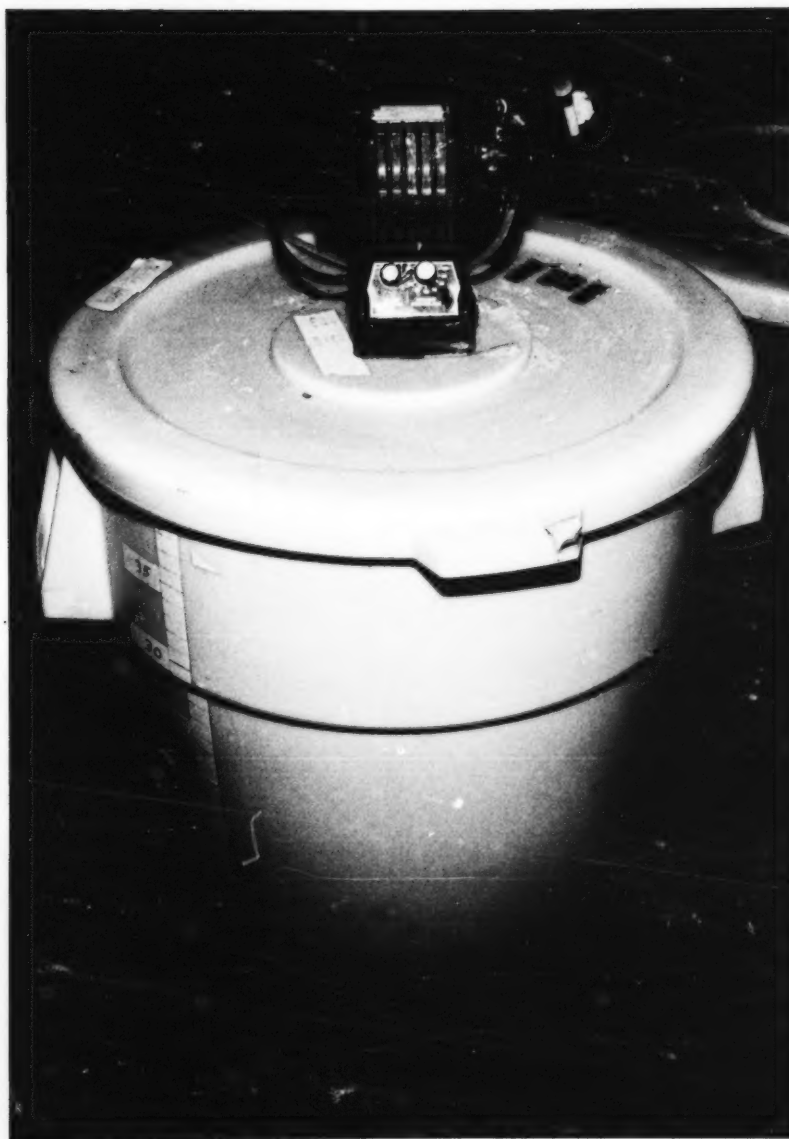


Figure D-5. Chemical feed system.

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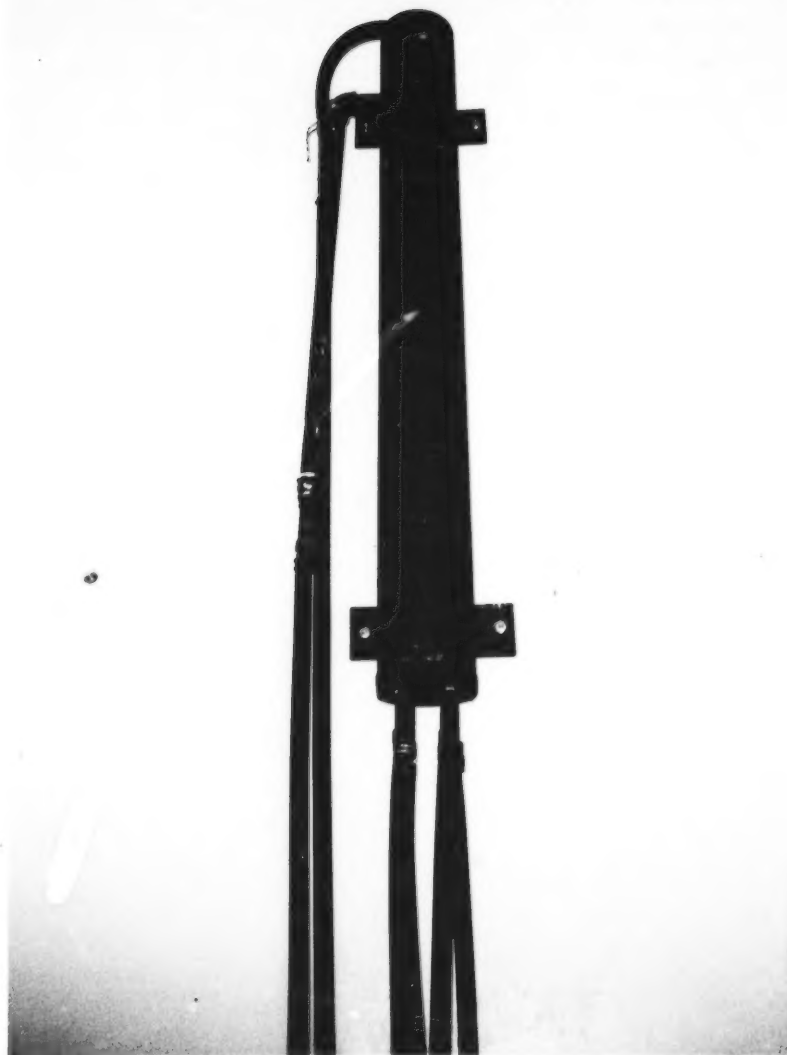


Figure D-6. Constant head reservoir.

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